Organisation for Economic Co-operation and Development

ENV/WKP(2022)4

Unclassified **English - Or. English**

Digitalisation for the transition to a resource efficient and circular economy

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Authorised for publication by Rodolfo Lacy, Director, Environment Directorate.

Keywords: circular economy, resource efficiency, digital technologies, circular business models, market failures, rebound effects

JEL Codes: L22, L23, O14, Q53, Q55, Q58

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Abstract

Digital transformation is increasingly recognised as a means to help unlocking the benefits of more inclusive and sustainable growth and enhanced social well-being. In the environmental context, digitalisation can contribute to decoupling economic activity from natural resource use and their environmental impacts. Digital technologies, such as artificial intelligence, blockchain, the internet of things and cloud computing, facilitate the transition to a more resource-efficient and circular economy, by helping to overcome obstacles that stand in the way of the large-scale deployment of greener business models, as well as a more effective delivery of circular economy policies. Besides the positive transformations, there are also risks of potentially negative consequences that could result from a broader uptake of digital circular economy.

This paper takes stock of the implications of digitalisation for the transition to a resource efficient and circular economy. Particularly, the paper provides insights into how digitalisation may fuel circular business models in the private sector, and discusses the role of digital technologies in addressing some important market failures that stand in the way to scaling up circular activities (such as imperfect information and transaction costs). It also offers a public sector perspective, by exploring how digital technologies support effective delivery of circular economy policies, enabling better policy design, reshaping government-citizen interaction and improving implementation of policies. Additionally, the paper maps potential unintended consequences of the digital circular transition, including general risks related to data, security, privacy and transparency, as well as rebound effects and unexpected regulatory interventions. To accelerate the uptake of digitalisation for transitioning towards a resource efficient and circular economy, an enabling policy framework that promotes digitally enabled circular activities while mitigating the risks that these bring with them, will need to be established.

Keywords: circular economy, resource efficiency, digital technologies, circular business models, market failures, rebound effects.

JEL codes: L22, L23, O14, Q53, Q55, Q58.

Résumé

Il est reconnu aujourd’hui que la transformation numérique constitue un levier vers une croissance soutenable et plus inclusive, ainsi que vers un bien-être social accru. Dans le contexte environnemental actuel, la numérisation peut permettre de dissocier l’activité économique de l’utilisation des ressources naturelles et de ses conséquences sur l’environnement. Les technologies numériques telles que l’intelligence artificielle, le chaînage par blocs, l’internet des objets et l’infonuagique, en permettant de surmonter les obstacles au déploiement à grande échelle de modèles économiques « verts » ainsi qu’en rendant plus efficace la mise en œuvre de politiques en faveur de l’économie circulaire, facilitent la transition vers une économie sobre en ressources et circulaire. Cependant, à côté de ses transformations bénéfiques, il existe aussi des risques relatifs à de potentielles conséquences négatives associées au développement plus large de l’économie circulaire numérique.

Ce rapport dresse un bilan des implications de la numérisation pour la transition vers une économie sobre en ressources et circulaire. En particulier, l’article propose un éclairage sur la manière dont la numérisation peut aider les modèles économiques circulaires dans le secteur privé. Il discute du rôle des technologies numériques dans le traitement de défaillances de marché importantes qui entravent la montée en puissance des activités circulaires (par exemple l’information imparfaite et les coûts de transaction). Il offre également une perspective du point de vue des pouvoirs publics en explorant la manière dont les technologies numériques, en permettant une meilleure conception des politiques publiques, en restructurant les interactions entre les administrations et les citoyens, et en améliorant l’implémentation des politiques publiques, soutiennent effectivement la mise en œuvre de politiques d’économie circulaire. Par ailleurs, l’article recense les potentielles conséquences indésirables de la transition circulaire numérique, incluant les risques d’ordre plus général liés à la sécurité des données, le respect de la vie privée et la transparence, ainsi que les effets de rebonds et les interventions réglementaires imprévues. L’accélération de la numérisation pour la transition vers une économie sobre en ressources et circulaire requiert ainsi la mise en place d’un cadre d’action publique adapté promouvant des activités circulaires reposant sur le numérique, tout en limitant les risques qui y sont associés.

Mots clés : Économie circulaire, efficacité des ressources, technologies numériques, modèles économiques circulaires, effet rebond.

Classification JEL : L22, L23, O14, Q53, Q55, Q58.

Acknowledgements

This working paper is an output of the OECD Environment Policy Committee (EPOC) and its Working Party on Resource Productivity and Waste (WPRPW). It has been authored by Eva Barteková, with support in conceptualisation, analysis, methodology and supervision by Peter Börkey. Frithjof Laubinger developed an initial scoping paper and also reviewed later versions, while Atsumi Kainosho helped with initial research. Aziza Perriere, Illias Mousse Iye, and Emily Seftel provided editorial assistance. The work on this report was conducted under the overall supervision of Shardul Agrawala, Head of the Environment and Economy Integration Division of the OECD's Environment Directorate.

The authors are grateful to delegates of the OECD Working Party on Resource Productivity and Waste (WPRPW) for helpful comments on earlier drafts of this paper, and for sharing experiences on policy implications of the digital transformation of circular economy. Furthermore, the authors are indebted to experts who provided their valuable time and insights to the report through interviews or written inputs, including: Jeroen Nagel (Rijkswaterstaat [RWS]), Ladislav Tvaruzek (VividEconomics), Karl Vrancken (VITO), Charlotte Cheynard (eBay Government Relations), and Alexandros Dimitropoulos (PBL Netherlands Environmental Assessment Agency).

The responsibility for the content of this publication lies with the authors.

This work was carried out with funding from the European Union. The views expressed in this report can in no way be taken to reflect the official opinion of the European Union.

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Executive summary

The past decades have witnessed unprecedented growth in global demand for raw materials. According to the OECD projections, global material use will further increase and more than double between 2018 and 2060, if no further policy action is taken. To reduce material consumption and offset the resulting environmental pressures, more stringent resource efficiency and circular economy policies are needed all along the value chain.

The large-scale deployment of circular business models is one of the means to decouple economic activity from natural resource use and its environmental impacts. Circular supply, resource recovery, product life extension, sharing and product service systems in particular, allow firms to create, capture, and deliver value through fundamental changes in production and consumption patterns.

However, the market share of circular business models remains limited. Recycling, remanufacturing and repair, sharing of spare capacity and provision of services instead of products account for only a minor share of the sectoral production. A number of market failures constrain the scalability of these models.

Digital technologies help to overcome some of the obstacles limiting the uptake of circular economy opportunities. Through their ability to monitor, interconnect and manage objects in the physical world electronically, digital technologies help unlocking the potential of circular business models.

Digital technologies can help to address market failures and to scale the transition to a resource efficient and circular economy

Information flows generated by digital technologies, such as artificial intelligence (AI), internet of things (IoT), big data analytics, cloud computing, blockchain, online platforms and 3D printing, can be considered as the main drivers of digital circular transition. Allowing to collect, manage and process data and information and to create knowledge (about material composition of products, their origin and properties, their location, condition and availability, as well as conditions for their manufacturing, maintenance, dismantling and recycling), digital technologies enable automated decision making, optimised asset sharing, reduced transaction costs and simplified prototyping. They thereby help to overcome some of the barriers to scaling up circular economy. One of these are market failures, which impede the well-functioning markets through inefficient allocation of resources.

There are four categories of market failures, hindering the uptake of circular economy, which digital technologies help addressing:

- **Imperfect information** triggered by asymmetric or inexistent information exchange between different actors along the value chain: This leads to inadequate traceability of products, components and embedded materials, as well as lack of trust in their reuse and recycling. Examples of digital technologies reducing information asymmetries include digital passports, which provide an auditable record of a products' journey from design to end-of-life stages. They enhance understanding of the composition of end-of-life products and facilitate their disassembly in the scrapyard, allowing for improved recovery of materials and their potential reuse.

- **Transaction costs** related to finding and bargaining with customers and suppliers, as well as those related to uncertainties around waste generation and composition: They may slow down the adoption of some of the service models, incurring higher capital costs, maintenance fees and virgin material consumption levels. Examples of digital technologies lowering transaction costs include digital sourcing platforms combined with AI and blockchain, which help to create a transparent and reliable source of secondary and excess materials and thereby facilitate their exchange across different sectors and industries. Similarly, asset sharing platforms integrated with IoT, big data, cloud computing and AI, enable generating data on market demand and supply of shared assets. This in turn facilitates sharing of both household items and industrial equipment.
- **Consumption externalities and risk aversion** towards the quality of final goods produced from secondary raw materials: Consumers' misperceptions about low relative qualities of some secondary materials might prevent these to be used in applications for which they are perfectly appropriate. To help reduce consumption externalities, digitally validated quality control systems with end-to-end tracking of the material flows address uncertainty about quality and availability of recycled materials. Such technology is currently under development for recycled plastic material across the packaging and building B2B-supply chains.
- **Technological externalities** related to recovery and decentralised manufacturing of components or final products: These create complexities in optimising circular design and consumption and hinder efficient dismantling and material recovery. Computer aided design (CAD) used in 3D printing technology, mitigates technology externalities by facilitating the creation, manipulation and analysis in the process of designing products with complex geometries. Similarly, building information modelling (BIM) software used in the construction industry, enables digital design of construction projects. By facilitating design optimisation, both solutions enable easier disassembly and recycling of products and constructions. Moreover, they provide insights into functional considerations, environmental impact and cost predictability of buildings

Digital technologies can also help to improve the design and implementation of circular economy policies

Besides facilitating the uptake and expansion of circular activities in the economy, digital innovations can be a useful tool in policy making. The application of digital technologies holds the potential to significantly improve efficiency and effectiveness of circular economy policies, by enabling innovative policy design, monitoring and evaluation, as well as enforcement. Examples of improving the three aspects of policy making include:

- **Policy data and analysis:** Access to unprecedented volumes of crowdsourced and online data collected through digitalisation enables policy makers to identify priority areas and to make data-driven policy decisions. For instance mobile applications, online platforms and public databases can support marine litter prevention.
- **Policy design and reshaped government-citizen interaction:** Digitalisation brings new instruments for governments to experiment with more effective design and evaluation of policies. For instance, smart waste collection, enabled by IoT and sensors, helps increasing efficiency and improving quality of waste collection services. Another example are online platforms, which enable civil servants to tap into collective intelligence for better-informed decisions (such as crowdsourcing policy priorities in waste management), while fostering positive relationships with citizens and businesses.
- **Improved implementation:** Increased possibility to monitor outcomes through availability of data and information enables more effective enforcement and targeting of existing policies. For instance, the combinatory power of online systems, machine learning and AI can be used to detect fraudulent

behaviours and ensure compliance, by facilitating the tracking and reporting of hazardous waste shipments.

But the digitalisation of the circular economy also generates a number of potential risks that need to be addressed

While the digitally enabled circular economy can lead to many positive transformations, there is also a risk of potentially negative consequences that could result from a broader uptake of both digital technologies and circular business models.

The risks associated with the use of digital technologies include:

- The more general risks related to **data security, privacy, ownership, transparency and use** are amplified, which is similar to other areas where digital technologies are being applied at scale.
- Other risks arise from the **resource consumption** linked to digital technologies or to the materials that they use. For instance, wide-scale use of blockchain and AI in circular economy applications requires data processing that is energy intensive. Similarly, 3D printing may lead to the use of materials that are hard to recycle.

Additionally, there are four types of unintended consequences of the digital circular economy:

- **Environmental:** Increased levels of production and consumption of digital goods (e.g. electronics) and services (e.g. energy / material intensive services, such as cloud computing), might offset the increases in production and consumption efficiencies gained through digitalised circular economy activities. This is known as the rebound effect.
- **Social:** Changes to business models triggered by digital technologies are expected to profoundly impact employment across some sectors, in terms of job creation, job displacement and job quality, as well as widening skills gap.
- **Economic:** Digitalisation might also amplify some pre-existing market distortions, such as barriers to entry and market concentration. In particular, small and medium sized enterprises (SMEs) and start-ups might be facing more difficulties in accessing and using data, information and knowledge generated by these technologies, compared to large players.
- **Regulatory:** The fast expansion of digital circular business models may lead to unexpected regulatory intervention. Aiming to protect users and citizens, regulation might limit the growth of some of the sharing business models (such as ride hailing and temporary lodging platforms). At the same time, digitalisation may also lead to weakening existing regulation. For instance, the expanding use of international market places may induce free-riding in extended producer responsibility (EPR) schemes, which are aimed at organising and financing the end-of-life management of some product groups.

Key implications for policy making

To accelerate the uptake of digitalisation for transitioning towards a resource efficient and circular economy, an enabling policy framework is required. This needs to create favourable conditions for large-scale digitalisation of the circular economy and mitigate potential unintended consequences. Some of the key elements of such policy framework are:

- **Addressing the systemic risks of digital technologies that may otherwise stand in the way of their wider adoption in the market.** More specifically, policies for better data governance and access to data need to address digital security, balancing privacy with openness, and promoting better measuring and valuing of data.

- **Supporting the development of circular economy relevant digital applications through R&D policies and programmes to speed-up the transformation.** Private investment should be targeted through economic instruments, while public funds could focus on funding initial phases of R&D, complemented with blended-finance models and green public procurement. In general, policies need to encourage more open-source multi-stakeholder collaborative R&D to foster innovation in circular business models enabled by digital technologies. Additional investment into shared data infrastructure might contribute to further scaling new business models.
- **Supporting the development of standards and harmonised data protocols that are crucial for the use of digital technologies in the circular economy.** Encouraging open-source interoperability of data and globally distributed data architecture could help to overcome the challenges around accessing, collecting, processing and sharing large sets of data records and computing infrastructure across private and public owners both within and across countries.
- **Addressing the risks linked to unintended consequences of the digital circular economy scale-up.** To mitigate the unintended consequences of the increased uses of digital technologies, policies should focus on integrating circularity aspects into digitalisation, addressing material and energy efficiency in their design. To alleviate potential environmental rebound effects, policies should aim at encouraging green design and improving social perception of pre-owned or recycled products. In response to concerns about labour market transition triggered by digital circular economy disruptions, training workforce with future proof skills and regulating new working arrangements will become essential. With regard to regulation, flexibility in regulatory approaches will be required to balance competing considerations of consumer protection with too much regulation.
- **Encouraging circular economy policy making using digital technologies and the data they generate.** Governments should consider exploring data-driven approaches to their foresight capacities, to better anticipate environmental and societal trends and needs, and as such to increase efficiencies and better target circular economy policy making.

1 Introduction

Digitalisation transforms economies and societies by changing the ways people interact with physical and virtual assets, businesses function and innovate, and governments design and implement policies (OECD, 2017[1]). Digitalisation is radically changing the nature of assets that generate value, the way their ownership is imparted and where the value is generated. Digitalisation and digital technologies therefore act as drivers of value creation within industries, with potential to transform entire value chains. In the environmental context, digital technologies can also contribute to facilitating a more resource-efficient economic system with reduced environmental impacts.

Recent decades have seen an unprecedented growth in demand for natural resources and materials, driven by continued economic convergence and population growth. Current projections show that material use is expected to double by 2060 (mainly driven by metals and non-metallic minerals), and to further exacerbate the economic and environmental consequences (OECD, 2019[2]).

Countries increasingly recognise the need to decouple economic activity from natural resource use and their environmental impacts. One of the channels through which decoupling can be achieved is the large-scale deployment of greener models of production and consumption. In this context, the concept of circular economy has been gaining increased attention on the global policy agendas (OECD, 2019[3]).

Circular economy helps to keep resources flowing within rather than through the economy, modifying flows of products and materials by means of three main mechanisms: closing resource loops, slowing resource loops or flows, and narrowing resource flows (McCarthy, Dellink and Bibas, 2018[4]). Circular economy therefore has the potential to reduce environmental pressures and risks of raw material supply shocks, as well as to contribute to economic expansion and job creation in some industries (OECD, 2019[3]).

The transition to a resource efficient circular economy[1] can be operationalised through circular business models, which allow firms to create, capture, and deliver value by way of fundamental changes in production and consumption patterns. A recent OECD report has identified five key business models.[2] These models can provide a business case for various circular activities, and could thereby facilitate the transition to a more resource-efficient and circular economy (OECD, 2019[3]).

However, the market share of circular business models remains limited. Recycling, remanufacturing and repair, sharing of spare capacity and provision of services instead of products typically account for less than 15% of sectoral production (OECD, 2019[3]). One of the key barriers to increasing the scalability of circular activities are market inefficiencies, such as incomplete information about product composition and conditions for maintenance and recycling, or transaction costs incurred when identifying sources of secondary and excess materials across sectors and industries.

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[1] For the rest of the paper, the term circular economy will be used to describe resource efficiency and circular economy processes related to lowering the rates of natural resource extraction and use throughout the value chain.

[2] The five circular business models identified along the value chain include: circular supply, resource recovery, product life extension, sharing and product service systems.

Information flows generated through digital technologies, such as artificial intelligence, internet of things, big data analytics, blockchain and online platforms (sometimes also referred to as *Industry 4.0 technologies*), help to overcome some of the market inefficiencies. Through their ability to monitor, interconnect and manage objects in the physical world electronically, these technologies allow collecting, managing and processing data and information and creating knowledge about materials, products and processes. Digitalisation of production therefore facilitates data driven decision-making in industrial production, optimising the performance of systems and processes, creating digitally enhanced goods and services, minimising waste, promoting longer life for products and supporting design for circularity (Valkokari et al., 2019[5]; OECD, 2017[6]; OECD, 2017[1]).

Digitalisation not only makes physical assets more intelligent, its combinatorial technologies also help changing the way value is created (Ellen MacArthur Foundation, 2016[7]; World Economic Forum, 2017[8]). Digital transformation reinforces shifts in consumption and production models, for instance by reducing transaction costs and risks associated with sharing models, facilitating product service systems through real time monitoring of product performance, and dematerialising products. It therefore helps accelerating the transition towards more circular systems throughout the private sector.

Digital innovation and uptake of digital solutions can also be leveraged by policy makers, to create greater efficiencies in providing public services, improving sustainability, and driving economic development. For instance, digitalisation holds the potential to enable innovative policy design, such as the introduction of smart waste management of volumetric tariffs for food waste.

While digitalisation of circular economy can lead to positive transformations across public and private sectors, it can also fundamentally challenge some of the long-standing approaches across public policy domains. For instance, potential unintended environmental consequences may arise from rebound effects, driven by increased demand for materials resulting from increased consumption of circular activities.

This paper intends to take stock of the implications of digital technologies for the evolution and uptake of circular economy. It does so by drawing together insights from existing literature on digitalisation and circular economy. Chapter 2 provides a brief discussion on digitalisation (with a more elaborate non-technical summary of the key digital technologies provided within the Annex on Digital Technologies). Chapter 3 provides an insight into how digitalisation may fuel circular business models in the private sector, and discusses the role of digital technologies in helping to address market failures for the uptake of circular activities. Chapter 4 offers a public sector perspective, exploring how digital technologies support effective delivery of circular economy policies. Chapter 5 maps potential unintended consequences of the digital circular transition, while Chapter 6 identifies key policies for digital circular economy innovation and uptake.

2 Digitalisation and digital technologies

Digital transformation has been widely recognised as one of the drivers of economic and social change. Seen as a means to help unlocking the benefits of more inclusive and sustainable growth and enhanced social well-being, digitalisation has now taken root on the agendas of national governments and international fora, such as the G7, the G20 and the OECD Ministerial events (OECD, 2017[1]; OECD, 2019[9]).

Digitalisation of production (also referred to as *Industry 4.0*, or *fourth industrial revolution*), concerns the use of emerging, and often interconnected digital technologies, which enable new and more efficient processes in industrial production, and generate digitally enhanced traditional and new goods and services, products and business models (OECD, 2017[1]; OECD, 2017[6]).

Digitalisation has been driven by two overarching technological trends, *digitisation* and *interconnection,* complemented by a growing ecosystem of inter-related technologies. Digitisation is the conversion of an analogue signal conveying information (such as sound, image, or printed text) to binary bits and digital data. This digital data can be used (i.e. processed, stored, filtered, tracked, duplicated and transmitted) infinitely by digital devices without degradation, at high speeds and at negligible marginal cost. Growing interconnections, among others by means of the Internet, allow this data processing to occur globally (OECD, 2017[1]).

A wide range of new products, applications and services, which apply digitisation and interconnectivity in a number of different ways, have emerged. They form an ecosystem of digital technologies driving the economic transformation. Previous OECD reports have identified the following technologies being part of this ecosystem (OECD, 2017[1]; OECD, 2017[6]; OECD, 2018[10]):

- *Internet of Things (IoT)* - connects objects and sensors that gather and exchange data;
- *Big data analytics* - permits processing and interpreting large volumes of data;
- *Artificial intelligence (AI)* - allows machines to perform human-like cognitive functions;
- *Blockchain* - facilitates transactions and interactions through decentralised and immutable information exchange;
- *Cloud computing* - offers services of computing resources over the Internet;
- *Online platforms* - enables innovative forms of production, consumption, collaboration and sharing, through interactions among and between individuals and organisations.

Besides connectivity and computing, and analytics and intelligence, digital technologies also enable digital physical transformation. For instance, *additive manufacturing* (also known as *3D printing*) builds products by adding material in layers, often using computer-aided design software. It offers a customisable alternative to traditional mass-production technologies, allowing to print multi-structure multi-material objects (OECD, 2016[11]; OECD, 2017[6]). Other technologies transforming global production systems include autonomous and *collaborative robotics*, *mechatronics*, and *photonics* (World Economic Forum, 2017[8]).

Although very different in terms of their forms, knowledge bases and application areas, digital technologies can be characterised by some common traits (identified by the OECD as *vectors of digital transformation*) (OECD, 2017[1]). Firstly, digital products enable firms to scale very quickly, often with few employees, tangible assets or a geographic footprint. Secondly, digitisation of functions facilitates the management of complexity in products and services. Thirdly, the intangible and machine-encoded nature of digital technologies allows firms and individuals to share their capital and to decouple value from specific geographical locations. Finally, digital transformation enables users to build networks, and facilitates the creation of digitally empowered multi-sided markets where value creation, transaction and interaction occur regardless of location and borders.

Some applications of digital technologies have already reached scale, while others are still in early stages of development. Each of the technologies may have disruptive effects on individual consumer behaviour, on the economy as a whole, and on the transition to a resource efficient and circular economy in particular. Additionally, many of the digital technologies do not function in isolation, but are combinatorial, and function as part of the ecosystem that underpins the digital transformation (OECD, 2017[1]). For instance, the combinatorial power of online platforms, blockchain and AI, enable digital sourcing platforms designed to facilitate exchange of products and materials at their highest value reuse opportunity.

The non-technical overview of the key trending digital technologies that have been identified by previous OECD reports (i.e. IoT, big data analytics, AI, blockchain and cloud computing), in addition to other digitally-enabled technologies that are relevant for the uptake of circular business models (i.e. online platforms and 3D printing) can be found within the Annex on Digital Technologies.

3 The role of digitalisation in lifting obstacles to a resource efficient and circular economy transition

3.1. Digitalisation facilitates data generation and knowledge creation

Digitalisation is disrupting the parameters of the current economic system. It does so by transforming value chains, changing the structure and operation of markets, enabling creation of platforms and ecosystems, affecting consumer behaviour and how relationships are developed, maintained and advanced, increasing the value retention, and mitigating some of the environmental externalities. Combining physical and virtual assets, digital transformation acts as a driver of value creation across value chains and reinforces the shifts in consumption and production models.

Digital technologies enable physical objects to sense, record and communicate information about themselves and their respective surroundings, regarding location, condition, and availability (therefore the labelling *intelligent assets*) (Ellen MacArthur Foundation, 2016[7]). Through their ability to monitor, interconnect and manage objects in the physical world electronically, digital technologies allow to: *collect, manage and process data and information* and to *create knowledge* about material composition of products, their origin and properties, their location, condition and availability, as well as their respective manufacturing processes and conditions for maintenance, dismantling and recycling.

Information flows generated by intelligent assets can be considered as one of the main drivers of digital transition, creating significant economic opportunities. Digital technologies facilitate data-driven decision making and allow optimising performance of systems and processes. They help, creating and capturing value in new ways throughout assets' life-cycles and facilitate their sharing or leasing across multiple sectors, businesses and individuals (Ellen MacArthur Foundation, 2016[7]).

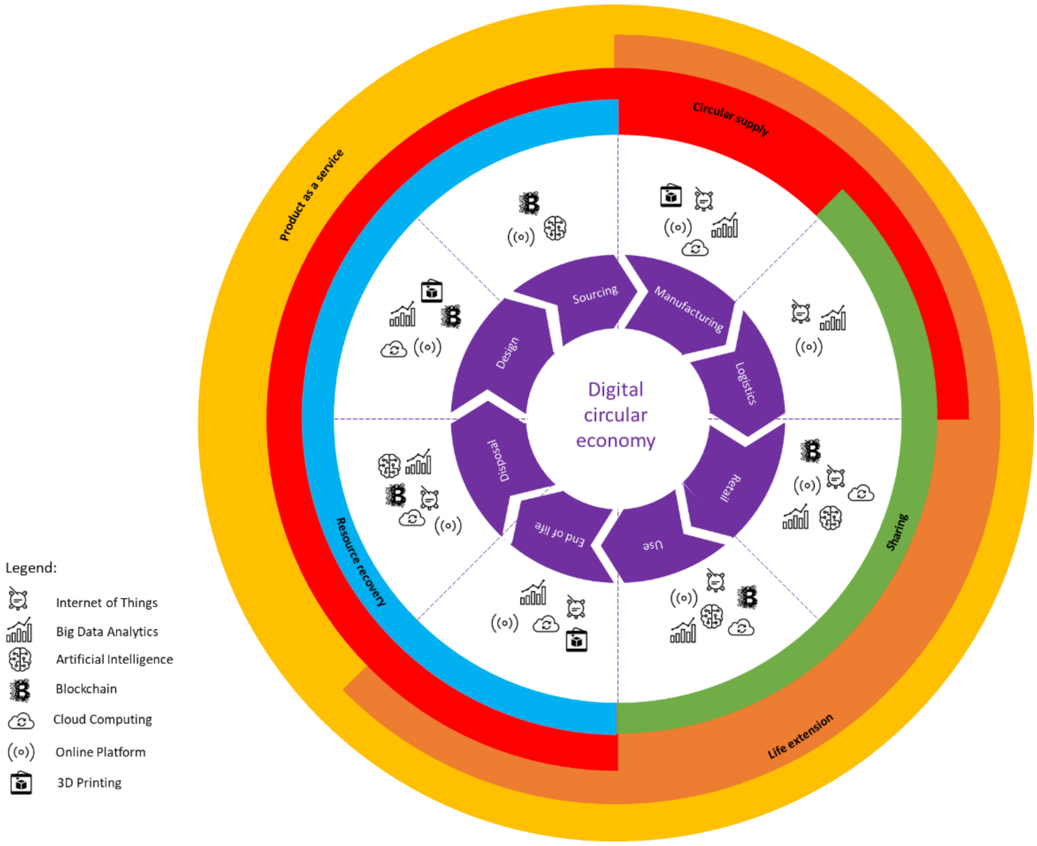
3.2. Access to data, information and knowledge helps to unlock the potential of circular business models

Availability and flow of information within and across value chains has been identified as instrumental to unlocking opportunities for circular economy (Climate-KIC, 2018[12]). Data collection, information management and knowledge sharing facilitated by digital transformation make circular business models operational, enable the development of new and improve the business case for existing circular economy activities. For instance, they help reducing transaction costs and risks associated with sharing models by facilitating interactions through decentralised and immutable information exchange, facilitate product service systems through real time monitoring of product performance, and enable product dematerialisation through replacing physical with virtual online content (Valkokari et al., 2019[5]; Ellen MacArthur Foundation, 2016[7]; OECD, 2019[13]).

Circular business models in turn, allow firms to create, capture, and deliver value through fundamental changes in production and consumption patterns. They thereby facilitate the transition to a more resource efficient and circular economy. A recent OECD report has identified five key business models that can provide a business case for the different circular activities (OECD, 2019[3]): circular supply; resource recovery; product life extension; sharing; and product service system.

Figure 3.1 maps digital technologies facilitating the scale-up of individual circular business models along the value chain. The inner and outer circles represent individual value chain stages and circular business models, respectively. They are connected through the central circle illustrating the (combinations of) enabling digital technologies.

Figure 3.1. Digital technologies facilitating the scale-up of circular business models



Note: Most of the time it is the combinatorial power of individual technologies that facilitates the scale-up of circular business models. It is not possible to single out / quantify the magnitude of their individual contribution.
Source: Own elaboration.

Different types of data, information and knowledge are necessary to facilitate different circular business models operating at different stages of the value chain. For instance:

- *Sharing models* (typically deployed in logistics, retail and use stages of the value chain) are largely facilitated by matching asset providers with consumers through personalised search, recommendation systems, smart price setting and secure exchange of value. These functionalities are enabled by data on location, condition and availability of shared assets, as well as knowledge about consumer behaviour and preferences, generated through a combination of IoT, cloud computing, machine learning, AI and blockchain technologies.

- *Product life extension models* (which extend the coverage of sharing models to include also manufacturing and end-of-life stages of products) require data on condition and end-of-life of products, parts and equipment, as well as information on material durability and repair, in order to enable products, components and materials to remain within the economy longer. While IoT, big data and AI allow jointly to determine the condition of in-service equipment at the use stage, the combinatorial power of big data and AI enable designers to take better decisions at the design stage.
- On the contrary, *circular supply models* are largely driven by data on origin and composition of products and materials, accompanied by information about processing, instructions for repair and conditions of recycling. Blockchain technology, which enables tracing of material origin from design, through sourcing, to manufacturing and disposal, allows recording material types and grades sold, collected and treated, and thereby mitigates the information gap between upstream and downstream stakeholders.
- Overlapping with circular supply, *resource recovery models* capture the production of secondary raw materials from waste streams through recycling or industrial symbiosis. To be operational, they necessitate data on collected and sorted quantities, and on availability and reusability of materials, as well as information on components and their recyclability. These can be sourced through IoT equipped collection bins, AI driven logistics systems, machine learning-backed product identification and value assessment capabilities at waste collection stations and online platforms facilitating digital sourcing of materials for reuse.
- Finally, the *product service system business models* combine a physical product with a service component all along the value chain. In order to provide a large scale access to services associated with a particular product, service or equipment (without actually owning them), data on their location, condition and availability, information on their uses and maintenance needs, as well as knowledge about consumer preferences and behaviour are required. These can be sourced through smart services enabled by IoT, AI, big data and online platforms operating on cloud-based infrastructure.

Business case-specific information management and knowledge sharing throughout the value chain are therefore important drivers for closing and narrowing resource loops and narrowing resource flows. Service models (i.e. sharing and product as a service) largely rely on data on location, condition and availability of (shared) assets and services, as well as on information and knowledge about consumers' preferences and habits. The other three models (i.e. circular supply, resource recovery and product life extension) necessitate predominantly data and information on product lifecycle, components availability, material compositions and specifications, as well as instructions for end-of-life and disposal handling.

3.3. The scalability of circular activities is constrained by a number of market failures

Integration of data and information management across value chains is important for overcoming the barriers to scaling up circular economy. Such barriers are related to deeply-rooted linear practices, complex mixes of processes and materials, and lack of access to resources, collaboration between relevant actors, and regulation (European Commission, 2019[14]). Different non-financial barriers limiting the uptake of circular economy exist. Notably, *market failures* (also labelled *market inefficiencies*) impede the well-functioning markets (in this context circular economy) and thereby inhibit them to deliver efficient outcomes to society (van Ewijk, 2018[15]). For instance, the failure to internalise environmental externalities from raw material extraction and waste management (i.e. prices of final products failing to account for costs incurred by air, land and water pollution from primary material production and their end-of-life management) lead to suboptimal consumption of such products, and have negative consequences for secondary material recovery markets (OECD, 2006[16]).

Various market failures relevant to resource efficiency and circular economy have been identified within existing literature. These range from environmental externalities and insufficient provision of public goods (including technological externalities), through insufficient competition (driven by high transaction costs, lack of confidence, and consumer risk aversion), to imperfect information and split incentives (Ellen MacArthur Foundation, 2015[17]; van Ewijk, 2018[15]; OECD, 2006[16]). While all these inefficiencies are important for markets in general, the analysis in this paper focuses predominantly on four categories of market failures that are particularly impeding the uptake of circular economy:

- *Imperfect information* related to condition and availability of components and products, composition of waste streams, as well as quality of secondary materials;
- *Transaction costs* related to finding and bargaining with customers and suppliers, as well as those related to uncertainties around waste generation and composition;
- *Consumption externalities* and *risk aversion*[3] towards quality of final goods produced from secondary raw materials;
- *Technological externalities*[4] related to resource recovery and decentralised manufacturing of components or final products.

3.4. Digital technologies can help to address market failures and to scale the transition to a resource efficient and circular economy

Different data, information and knowledge might be required for solving different market failures. By enabling access to and enhanced transparency of *data collection, processing, storing and analytics* about materials, components, processes, products and services, as well as *information and knowledge creation* for automated decision making, optimised asset sharing, reduced transaction costs and simplified prototyping, digital technologies facilitate and scale the transition towards a resource efficient and circular economy. Depending on the interplay between a specific ecosystem of digital technologies and individual circular activities, digitalisation may improve the business case for already existing activities (such as personalised search, predictive analytics or smart price setting), or prompt new circular activities (such as collaborative cloud manufacturing or predictive maintenance).

Each of the digital technologies, their combinatorial power, and the types of data, information and knowledge they help to generate, collect and process, may have different implications for removing specific market failures that negatively affect the scalability of circular activities. The three dimensions of this *market inefficiency-digital technology-circular activity nexus*, along with selected examples of how businesses integrate digital technologies into their circular economy activities to solve specific market failures, are collected illustrated in Figure 3.2. A synthesised overview of the nexus is presented within Table 3.1, while a more elaborate discussion is provided in the following sub-sections.

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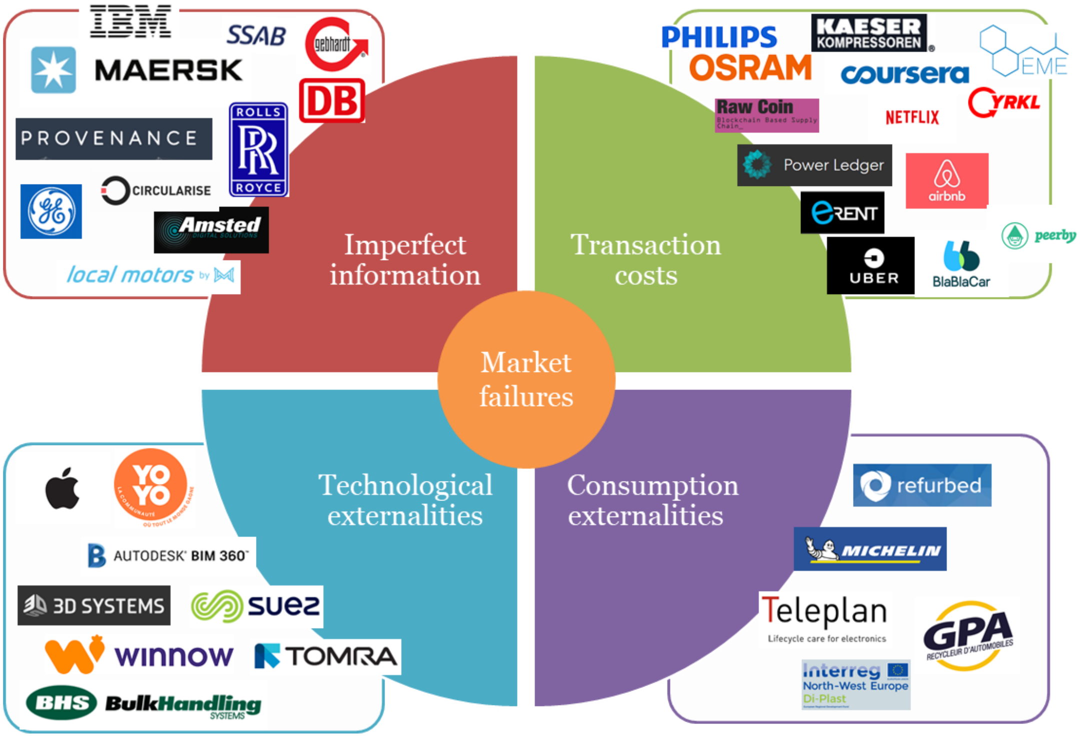
[3] An earlier OECD report investigating the inefficiencies in recycling markets defines consumption externalities and risk aversion as “perceived costs associated with the quality of final goods derived from secondary materials relative to those derived from virgin materials” (OECD, 2006[16]).

[4] An earlier OECD report investigating the inefficiencies in recycling markets defines technological externalities related to products as “complexity of recycling due to the technical characteristics of the recyclable material and products from which secondary materials are derived” (OECD, 2006[16]).

Figure 3.2. Market failures impeding the uptake of the circular economy



Note: This is not an exhaustive list of private sector initiatives integrating digital technologies along their circular activities.
Source: Own elaboration.

3.4.1. Digital technologies addressing imperfect information

Inadequate traceability of products, components and embedded materials, and lack of trust in their reuse and recycling, are largely triggered by asymmetric or inexistent information exchange between different actors along value chains. Information related to condition and availability of components and products, composition of waste streams and quality of secondary materials is often incomplete, asymmetric, or altogether missing.

Information asymmetry on material composition of products, their respective properties, processing and manufacturing, as well as instructions for repair and recycling, leads to inefficient disassembly of products in scrapyards and suboptimal recovery of secondary materials. This inhibits buyers from evaluating the actual quality of waste and potentially drives sellers to market secondary materials with lower quality attributes.[5] Imperfect information might ultimately prevent materials to be directed towards their highest value-added potential, or undermine their market altogether (OECD, 2006[16]). More specifically, the rate of reuse of materials is hampered by insufficient information on material authenticity and origin (in terms of responsible sourcing), as well as quality (in terms of presence of alloy contaminants in metals, or potential presence of hazardous materials in demolition waste). On a different level, waste collection and sorting are often lacking efficiency due to missing information on the status and functionality of recycling containers (such as waste levels, or condition of bins).

On the level of components, inadequate information about the condition of parts of equipment and their required maintenance and repair can increase cost and material inefficiencies for both manufacturers and

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[5] Such *adverse selection* is particularly relevant for plastics and construction and demolition waste, where different materials are aggregated during the collection.

users. Additionally, missing data on the condition of individual parts and products for remanufacturing and for their decentralised manufacturing, prevent carrying out analytic repairs and remanufacturing where needed, or replacing individual parts on-demand. These lead to increased material consumption during manufacturing and downtime costs of equipment during use phases. Digital technologies help to reduce information asymmetries in a number of ways.

Traceability to inform about the origin, quality and authenticity of products and materials

The combination of blockchain and cloud technologies enables better *end-to-end traceability of certifications* along the value chain, protecting producers' reputation and informing consumers about quality, origin and authenticity of products (Provenance, 2015[18]). For example, a blockchain-based pilot project may help to solve tracking issues of cobalt along the electric vehicle battery value chain, allowing to trace the metal from the mine and smelter in China through the cathode and battery plant in South Korea all the way to the Ford plant in the United States (Lewis, 2019[19]). Additionally, the project is also exploring possibilities of using AI to identify the origins of cobalt through chemical analysis of smelting processes.

Other solutions for improving the fragmented and proprietary character of information flow along value chains are smart contracts, backed by blockchain-based communication protocols, QR codes and RFID tags attached to materials, components and final products. *Smart questioning* (which allows stakeholders to ask product-related questions and receive trusted answers based on smart contracts) and *internet of materials* (such as SmartSteel 1.0, which allows customers to scan products and access raw material-related information from mill to end products) are both examples of creating an open-source decentralised database of digital identity of physical materials, components and products. They help creating trust and transparency without giving up confidential business information, and thereby turning the threat of losing competitive advantage to an asset of collaboration (Circularise, 2019[20]; SSAB, 2018[21]).

Materials parsimony for easier looping back into manufacturing process

Lack of information on material composition of products and parts for further reuse, repair and recycling can be overcome at the design stage through *materials parsimony*. Minimising the different types of materials used in manufacturing of products contributes to standardisation, which in turn makes the looping of materials and products within the system easier. It simplifies sourcing and manufacturing and drives down the material demand and costs. It also makes product maintenance, reuse, remanufacturing and subsequent end-of-life collection, sorting and recycling easier. Such environmentally sustainable product lifecycles are enabled through 3D printing, which can create complex parts and products using a single material. Material choice permitting, 3D printing allows up to 80% of the raw material to be collected and looped back into the manufacturing process at the end of automobile's life. For instance, in automobiles manufacturing, Local Motors were able to 3D print 80% of the parts from a monomaterial, what helped them reducing the number of components and materials from thousands to dozens (Unruh, 2018[22]).

Component and product tracking for maintenance and repair

Digital copies of complex physical products, services or processes can make up for the missing information during maintenance and repair. *Digital twin* (which represents a digital proxy of a physical world) generates real-time big data, which is collected through sensors attached to smart components and analysed by AI and machine learning within the cloud. The benefits of monitoring the status and the position of components and specific product uses include: timely identification of problems preventing downtimes, facilitating product redesign and optimisation (through informed product configuration), improving consumer experience (by better understanding consumer needs) and possibly planning for future (through simulations in the virtual environment) (Marr, 2017[23]; Prox, 2018[24]; Cubiss, 2019[25]).

Once potential future failures are identified, *predictive maintenance* allows replacing the required component at the required time, detecting machine conditions that would otherwise lead to failures and estimating the amount of time before such failures occur. Predictive maintenance is based on big data collected through sensor technology and stored and analysed in the cloud through machine learning. An example of early identification of machine failure patterns in practice is in place at Rolls-Royce, which monitors in-service engines and overall planes' condition (Le Moigne, 2018[26]). Based on similar principles, Amsted Digital Solutions uses *condition-based machine learning-facilitated maintenance* to save maintenance costs, extend product life and improve supply chain flows (Felty, 2018[27]).

Condition-based remanufacturing and decentralised manufacturing

Condition-based manufacturing helps determining the extent of repair and securing the required replacement parts. More specifically, condition-based manufacturing, enabled by remanufacturing data and information on wear and tear of each component, allows determining whether serious repair is required (as opposed to a small brushing up or no repair at all). For analytic repairs and remanufacturing of diesel powered locomotive engines, General Electric makes use of industrial IoT (IIOT) and industrial cloud platforms, which enable rebuilding engines faster and in a more reliable and resource efficient way (IndustryWeek, 2019[28]).

To decrease the risk of potentially lengthy delivery times for replacement parts, *decentralised print-on-demand* enables to print parts locally and on demand. This not only speeds up the procurement process and allows customisation, it also reduces the logistics required to transport and store large inventories of spare parts, decreases material uses and minimises waste while production. For instance, the German railway company produces customised heavy replacement parts in-house, what eliminates the long waiting times (of up to 24 months) and the associated downtime costs (Deutsche Bahn, 2019[29]). They plan to introduce some 10 000 different spare parts in the near future, using 3D printing technology and construction templates from existing drawings or scanned objects.

Digital passports to support disassembly, reuse, and recycling

Digital passports (also labelled as *cradle to cradle passports*, or *material passports*) are database-backed digital reports that "travel" with physical products, provide an auditable record of their journey from design to end-of-life stages, and carry information on product compositions and embedded material types and grades. By improving the understanding on the composition of products, they facilitate disassembly process in the scrapyard, improved recovery of materials (enabling the mixed recyclate to keep quality, properties and value comparable to virgin materials) and increased potential for their reuse. Additionally, if delivered through blockchain technology, digital passports can ensure the immutability of data, create trust and remove asymmetric information along value chains. From a producer's perspective, digital passports also facilitate gaining greater control over materials throughout products life-cycles. For instance, Maersk uses digital passports to recover and sort steel from its decommissioned vessels more effectively, recycle it to a higher quality and reuse it for building new vessels (Ellen MacArthur Foundation, 2019[30]; EPEA, 2011[31]). The improved quality of scrap metal helps Maersk to reduce the dependence on virgin iron ore, keep capital costs down and potentially generate additional lines of income from re-selling recovered materials.

Tracking of waste for better collection and recycling

Smart waste management based on asset tracking enables better waste collection and recycling. This is facilitated by Radio Frequency Identification (RFID) tags (a combination of sensors, identification technology and internet connectivity). More specifically, when attached to waste and recycling containers, RFID tags help implementing pay-as-you-throw waste programs and optimising municipal waste collection in cities (Aclima, 2017[32]). Real-time data stored and processed in the cloud and exchanged between the cloud, trucks, containers, recycling facilities and secondary material retailers, helps to track the status of containers (in terms of their material content, fill levels, and need for repairs), oversee route management and fleet productivity, assure safety conditions, as well as more effective and cost-efficient sorting, reuse and recycling (Golubovic, 2018[33]).

3.4.2. Digital technologies lowering transaction costs

Besides information asymmetries, transaction costs are the most commonly cited market failure inhibiting the scale up of circular activities. These costs may be associated with price discovery (when price information is not available), search (when identifying counterparts in markets with small players, for instance in construction and demolition waste or low-volume plastic wastes), administration (related to transactions), or negotiation and bargaining (in markets with heterogeneous products, such as metals with different purities, oils and lubricants with different degrees of contamination, or mixes of plastics) (OECD, 2006[16]).

Search costs may be incurred when trying to match supply and demand for collaborative consumption and production within the sharing economy. These costs are driven by limited knowledge on market demand and supply of materials for reuse, availability of shared products and services, consumer preferences and behaviour, as well as manufacturing processes. Similarly, missing data on location, condition and availability of equipment and products might slow down the adoption of some of the service models (such as renting connected assets by hour), incur additional capital costs, maintenance fees and high energy and virgin material consumption levels. Digital technologies help to reduce these costs in several ways.

Asset sharing platforms

AI-enabled functions help to generate data on market demand and supply for shared assets and knowledge about consumer preferences, behaviour and habits, which are required for scaling up the sharing economy. Such functions can be leveraged through the combinatorial power of IoT generating big data, which is stored and processed in the cloud and subsequently fed into machine learning to ultimately produce matching algorithms for AI. Specific examples of *AI-enabled functions for the sharing economy* include Uber's tools for visualising datasets, open-source distributed learning framework and open-source streaming analytics platform, as well as Airbnb's machine learning package for building predictive pricing models (Inside Big Data, 2018[34]). Besides mobility on demand, carpooling and space sharing, renting equipment is another example of asset sharing platforms. For instance, Peerby allows users to rent household items from their neighbours (including delivery) (Peerby, 2015[35]). eRent is a business-users alternative for digital sharing and tracking of industrial equipment, such as machinery, site facilities, scaffolding, aerial platforms and security products (eRent, 2019[36]). Both business models have the potential to help reducing the need to manufacture new devices.

On a different level, *blockchain-powered platforms for peer-to-peer trading* use smart meters and smart contracts (which facilitate, verify, or enforce the performance of a contract) to offset emissions and track transactions related to environmental commodities, to enhance renewable energy uptake, and to solve excess of solar power generation. Power Ledger Platform is an example of an interoperable energy trading platform with a dual token ecosystem (Power Ledger Ltd, 2018[37]). For raw materials trading, a new blockchain and AI-enabled token empowers producers of raw materials and intermediary goods. Based on smart contracts, Raw Coin provides efficiency and transparency along the supply chain, ensuring origin, quality, compliance and handling of raw materials (Datarella, 2019[38]).

Dematerialisation and product as a service

Dematerialisation of assets, offering users product functionalities in form of services, is in practice facilitated by IoT, online platforms and cloud integration. Jointly, they enable connecting assets (the provision of which might otherwise be hampered by prohibitive search costs related to limited knowledge on their availability and consumer preferences and behaviours) and selling them as services. Examples of such assets range from renting water pumps by hour, to purchasing compressed air as a service or light as a service (e.g. by Kaeser Kompressoren, Philips, OSRAM), to cloud-enabled streaming of music, movies and education content online (e.g. by Netflix, Spotify, and Coursera). These subscription services have in common that they are on-demand. They thereby eliminate the need to purchase actual hardware and allow decoupling their use from the materials. Additionally, suppliers retain ownership of underlying assets, what ensures that the most value is extracted over the course of an asset's lifetime (through built-in traceability, recycling, upgrading and parts harvesting) (Lamarre and May, 2019[39]; Medium, 2017[40]; Schiller, 2017[41]) (Cubiss, 2019[25]; SmartCitiesWorld, 2016[42]).

Material exchange platforms

Digital sourcing platforms combined with AI and blockchain facilitate the exchange of products and materials at their highest value reuse opportunity across different industries. Reusing materials from other industrial processes requires knowledge about their availability and quality. While industrial symbiosis often occurs between two industrial producers in close geographic proximity within the same industrial / eco-innovation park, inputs to production might need to be also sourced at distance. In The Netherlands, the Excess Materials Exchange helps to create a transparent and reliable source of secondary and excess materials and to facilitate their exchange across sectors and industries (Excess Materials Exchange, 2019[43]). A similar secondary material market place for plastics, building material, paper, textiles, glass and electrical waste has been created in the Czech Republic (CYRKL, 2019[44]), while others are being set-up in a number of countries (including the US, Turkey and Vietnam).

Manufacturing as a service

Combining cloud computing with computer-aided product development and physical design and manufacturing environment, *cloud-based design and manufacturing (CBDM)* enables distributed manufacturing, on-demand resource sharing and cooperative work across value chains (Wu et al., 2015[45]). Manufacturing as a service is enabled by networked environment (including social media and search engines), big data and high-performance computing (collecting real-time design- and manufacturing-related data through IoT, smart sensors, and wireless devices), as well as by pay-per-use, resource pooling, and crowdsourcing. These service-oriented networked models allow configuring engineering designs of products and services and reconfiguring manufacturing systems through infrastructure-as-a-service (IaaS), platform-as-a-service (PaaS), hardware-as-a-service (HaaS) and software-as-a-service (SaaS) models. They ultimately facilitate open innovation with faster time to market, reduced costs, as well as improved information sharing, resource reuse and machine utilisation.

3.4.3. Digital technologies reducing consumption externalities

Some of the circular economy activities might be inhibited by the lack of consumer confidence related to secondary materials and second-hand products. More specifically, consumption externalities are driven by information failures on the buyers' side about suitability of secondary materials for the production of components and final products (i.e. their lack of understanding about degrees of substitutability between products derived from secondary and virgin materials) (OECD, 2006[16]). Consumers' misperceptions about low relative qualities of some of the secondary materials might prevent those materials to be used in applications for which they are perfectly appropriate.[6] This in turn locks consumers into volatile virgin material markets and exacerbates environmental (and possibly health) issues related to resource management.

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[6] For instance, metals manufactured from scrap might be a good substitute for most of the applications.

The concept of consumption externalities can also be extended to the lack of consumer confidence in the quality of final products and their reuse (such as refurbished electronics and car parts, or re-treaded tyres). Even if the probability of a refurbished product to fail might be marginal, consumers' risk aversion might disproportionately drive down the demand for such products (and the embedded materials), adversely impacting both recovery rates and use of remanufactured and refurbished products and equipment. Digital technologies help to reduce consumers' risk aversion in several ways.

Enhanced product information for more informed consumer choices

As discussed in Section 3.4.1, consumer confidence about quality, origin and authenticity of secondary materials can be restored by increasing transparency across value chains with the use of blockchain technology. By translating complex chains of custodies into distributed, immutable, digital trails, blockchain enables manufacturers, consumers and recyclers to confidently assert the circularity of their products (Circle Economy, 2018[46]). Another way of responding to uncertainty about quality and availability of supply of recycled materials and about lack consumer's awareness is through *digitally validated quality control system with end-to-end tracking of the material flow.* This necessitates sensors (to generate data), big data analytics (to provide information on the quality, amount and timing of the supply) and process management (to create processes for safe reuse). An example of such initiative is currently under development for recycled plastic materials across the packaging and building B2B-supply chains (which are the sectors with the highest plastic consumption). Di-Plast technology is piloted in Germany, the Netherlands and Luxembourg, with participation of companies from along the value chain (Interreg North-West Europe, 2018[47]).

E-commerce online platforms enable consumers to make more informed choices about refurbished products. More specifically, they help enhancing awareness about the existence of refurbished and remanufactured products and improving information flows and transparency on the characteristics of such products, components and materials. For instance the French automobile recycling company GPA refurbishes parts from dismantled cars and sells them through an online platform (eBay for business FR, 2019[48]). Another example is that of refurbished electronics, which are often restored to their original quality (their performance being comparable to that of new products) and are resold online at relatively lower cost (by up to 40% compared to new electronics) (Refurbed, 2019[49]). A more elaborate solution to providing information about the actual state of refurbished products is through an *automated objective grading technology*. This has been developed by Teleplan to improve the visual and mechanical inspection of physical and cosmetic condition of smartphones and other connected devices (Teleplan, 2019[50]). Using AI and image analysis technology, Optiline enables faster and more accurate measurement of traces of use (eliminating inconsistencies and human errors of a manual process) and detecting damages and defects. The high resolution pictures captured in the process can be used in production and repair environments, and also allow consumers to better understand the right value of refurbished devices and parts.

3.4.4. Digital technologies mitigating technology externalities

Technological externalities relate to the provision of infrastructure for recovery and reuse of secondary materials. Such externalities arise when a product is designed and manufactured to benefit primary markets, with reduced recyclability and no means by which processing facilities downstream could incentivise manufacturers to change the product design (OECD, 2006[16]). Technological externalities exist for some of the complex mixed wastes, such as multi-layer plastics, variety of resins and different colours of glass bottles, as well as pigments in paints and impurities in alloys. These might trigger higher separation and recycling costs, or might be incompatible with existing recycling techniques altogether.

During product design, manufacturing and use stages, lack of access to data on characteristics / composition, durability and recyclability of materials, components and products creates complexities in optimising circular design (i.e. design for easier disassembly and recycling) and circular consumption of products (i.e. connecting products with consumers). At the end-of-life stage, insufficient information about composition of waste streams and missing dismantling instructions accompanying individual products, are the main drivers hindering efficient dismantling, material recovery and waste reduction altogether.[7] Digital technologies can help tackling technology externalities at both ends of the product life cycle.

Enhanced tools and data for product and materials design

During product design and manufacturing stages, *computer aided design (CAD)* used in 3D printing technology helps to overcome information challenges related to composition, durability, modularity and subsequent disassembly and recyclability of customised products with complex geometries. More specifically, CAD can assist in the creation, manipulation, analysis and optimisation of the design of such products (SCULPTEO, 2019[51]). The body and frame of the Local Motors car is an example of a 3D printed product based on a CAD image file (discussed as an example of materials parsimony in Section 3.4.1) (3D Systems, 2020[52]). *Building information modelling (BIM) software* is used in the construction industry to enable digital design for construction projects. This digital platform for construction management ensures that information is recorded at each stage of the design, construction and operation of buildings (Designing Buildings, 2019[53]). Both solutions can contribute to design optimisation and provide insights into functional considerations of constructions and their environmental impact and cost predictability (Losavio, 2019[54]; Autodesk, 2020[55]).

In waste generation, *smart waste bins* present a solution to technological externalities hindering efficient dismantling, material recovery and waste reduction. For instance, Winnow Vision has designed an AI powered bin with a camera and smart scales to enable food waste tracking. Using machine learning to determine the exact types of waste, the resulting analytics drive a better understanding of what goes wasted, helping to minimise food waste and driving down restaurants' costs (Chapman, 2019[56]). A French-based start-up YOYO uses a *collaboration platform to reward plastic waste sorting* by individuals and companies (YOYO, 2019[57]). By collecting plastic bottles in neighbourhoods that are then directly shipped to a recycling site, the platform helps raising awareness among urban consumers about waste sorting, and at the same time it eliminates the challenges of missing information on waste composition. Some of the more advanced waste collection stations might also be equipped with product identification and value assessment capability with blockchain-based reward remuneration schemes (such as vouchers and discounts). A more holistic solution is represented by *smart centres for waste management and recovery*, which use real-time data for geolocation of collection trucks and containers, container fill levels and collection progress.

Some of the challenges in the dismantling process can be solved with the use of *recycling robots*. They are equipped with machine vision (to see the material), AI (to identify the material) and robotics (to pick the targeted items), which enables them to detect parts of products and strip those out safely and efficiently. Examples of such robots include Liam and Daisy, which disassemble old iPhones collected through the Apple GiveBack program and sort components (some of which are refurbished, or recycled for materials) (Opam, 2016[58]; Apple, 2018[59]). On a larger scale, ZenRobotics Recycler has been deployed by Suez Environment to safely and efficiently pick raw materials from construction and demolition waste (Recycling Today, 2013[60]). Recycling robots are also used for sorting municipal waste. For instance, BHS Bulk Handling Systems deploys a sorter with autonomous sorting decisions to separate out different metals or remove residues from a stream of PET bottles (Bulk Handling Systems, 2017[61]). A waste stream specific solution is piloted by TOMRA, which combines near-infrared (NIR) scan system with AI. Relying on intelligent packaging of products with invisible barcodes, its Sharp Eye technology allows determining what each product is made of and enables separating single-layer PET trays from PET bottles (TOMRA, 2019[62]). Early *prototype apps* are emerging to extend the uses of this technology to help consumers sort

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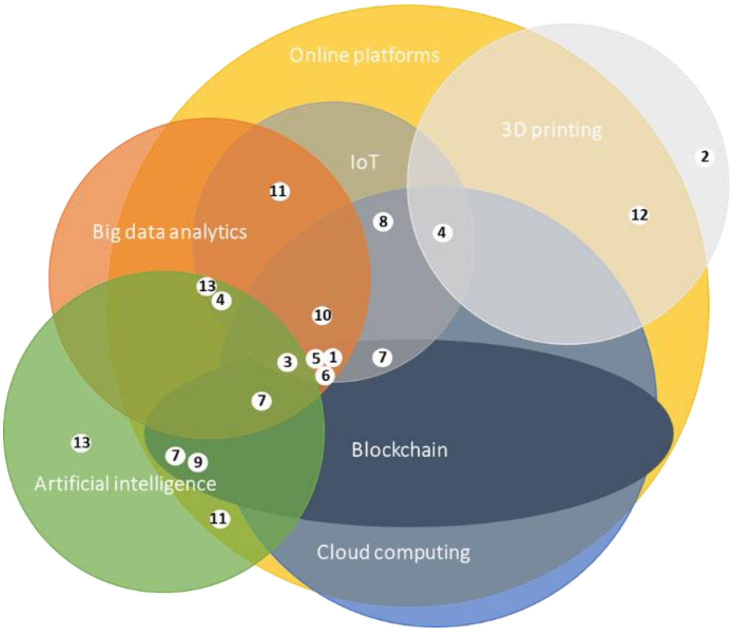
[7] Along with the lack of extended producer responsibility.

their recycling at home (Shaw, 2019[63]). All these initiatives contribute to increasing the material sorting, recycling and reuse rates.

The above discussion illustrates how specific digital technologies can contribute to addressing individual market failures and to contribute to scaling the transition towards a resource efficient and circular economy. Note that in some cases, the digital applications and their implications for circular economy described here might still be in their infancy, and their development is therefore subject to uncertainties. Some technologies may ultimately take a different path in the future than described here. Also, more often than not, it is the combinatorial power of digital technologies (rather than them acting in isolation), which enables the scaling of circular activities. This interdependence is illustrated in Figure 3.3, which presents the analysed ecosystem of digital technologies as an enabler to circular economy activities.

Figure 3.3. Examples of circular economy activities enabled by the combinatorial power of digital technologies



1. Traceability to inform about the origin, quality and authenticity or products and materials
2. Materials parsimony for easier looping back into manufacturing process
3. Component and product tracking for maintenance and repair
4. Condition based remanufacturing and decentralised manufacturing
5. Digital passports to support disassembly, reuse, and recycling
6. Tracking of waste for better collection and recycling
7. Asset sharing platforms
8. Dematerialisation and product as a service
9. Material exchange platforms
10. Manufacturing as a service
11. Enhanced product information for more informed consumer choices
12. Enhanced tools and data for product and materials design
13. Enhanced tools and data for dismantling and material recovery

Note: Note that this is an approximation of interdependencies between individual digital technologies.
Source: Own elaboration.

Table 3.1. Mapping of selected barriers to circular activities and corresponding enabling digital technologies

MARKET INEFFICIENCIES	DATA, INFORMATION, KNOWLEDGE MISSING	ENABLING DIGITAL TECHNOLOGIES	EXAMPLES OF CIRCULAR ACTIVITIES
IMPERFECT INFORMATION (AND CONSUMPTION EXTERNALITIES)	Insufficient information about the origin and quality of secondary materials; lack of data on collection, sorting, drying, and homogenisation of waste; lack of data on material composition of products, properties and processing; lack of information on manufacturing, instructions for repair and conditions for recycling.	Blockchain, online platforms / apps, big data, cloud computing, IoT	– *Cradle to cradle (or digital) passport* helps to identify different material types and grades during disassembly process in the scrapyard, and thereby allows improving recovery and reuse of materials, and reducing dependence on virgin iron (e.g. shipping steel recovery by Maersk). – *Supply chain mapping augmented for blockchain tracking for better product traceability*, allows to protect producers' reputation, to inform customers, or to ensure the quality and authenticity of goods (e.g. collaboration between Sourcemap and Provenance), as well as oversee responsible sourcing of raw materials (e.g. Ford and IBM cobalt blockchain project). – *Blockchain-based communication protocol* enables stakeholders to ask questions about a product and to receive trusted answers, based on smart contracts, interfaces, and unique identifiers within a decentralised application, i.e. data that has never been viewed, accessed or shared with anyone (e.g. Smart questioning). – *Internet of materials* allows customers to access raw material information, identifying products, examining material properties, downloading material certificates and giving feedback (e.g. digital identity of materials - SmartSteel 1.0). – *Asset tags attached to waste and recycling containers* help collecting data on when they are full, alerting haulers to deploy a vehicle to empty them, as well as ensure service verification and route management of waste vehicles, and inform waste sorters, recyclers, and secondary material retailers about the product and material type and composition (e.g. Radio Frequency Identification (RFID) tags for smart waste management).
		3D printing	– Promoting environmentally sustainable product lifecycles through *materials parsimony* enabled by 3D printing – this uses primarily one material to produce the bulk of a product, what thereby allows for easier material collection, sorting and looping back into the manufacturing process (e.g. Local Motors 3D prints 80% of its cars from a single material).
	Lack of data availability about needed maintenance and repair.	IoT, cloud computing, big data analytics, AI / machine learning, blockchain	– *Digital replicas of physical assets*, processes and systems, which include information on composition, health & safety, environmental data, facility information, procurement data and product usage (e.g. digital twin for operating conveyer systems at manufacturing sites by Gebhardt Fördertechnik). – *Predictive maintenance* allows to replace only the required part at the required time, detecting machine conditions that will lead to failure, and estimating the amount of time before that failure occurs, thereby allowing maintenance to be planned and avoiding costly downtime (e.g. Rolls-Royce monitors a planes condition and engines), and *condition-based maintenance* using sensors installed on components to collect large data sets necessary for machine learning to develop the algorithms to save maintenance costs, while extending product life and improving supply chain flows (e.g. Amsted Digital Solutions for freight rail).

MARKET INEFFICIENCIES	DATA, INFORMATION, KNOWLEDGE MISSING	ENABLING DIGITAL TECHNOLOGIES	EXAMPLES OF CIRCULAR ACTIVITIES
IMPERFECT INFORMATION (AND CONSUMPTION EXTERNALITIES)	Lack of data on the condition of individual parts and products for remanufacturing, and for their decentralised on-demand manufacturing.	3D printing, online platforms, cloud computing, IoT	– *3D printing of replacement parts locally, on-demand*, and by downloading design information from online marketplaces or construction templates from scanned objects (e.g. Deutsche Bahn - the German railway company producing difficult to obtain heavy replacement parts with the help of a 3D printer). – *Condition-based manufacturing* enabled by information on the wear and tear on each component in the engine, which helps to determine the wear and tear on each component and the need for manufacturing or remanufacturing (e.g. GE remanufacturing plant for remanufacturing of diesel engines for locomotives).
TRANSACTION COSTS	Limited information on the availability and quality of materials, as well as their highest value for reuse.	Online platforms, blockchain, AI	– *Digital sourcing platforms* facilitating exchange of products and materials at their highest value reuse opportunity (e.g. Excess Materials Exchange, CYRKL).
	Limited knowledge to facilitate collaborative consumption: lack of data on market demand and supply for shared goods and services, lack of knowledge about consumer preferences / behaviour.	Blockchain, AI, online platform	– *Smart meters and contracts through blockchain-powered platforms* for peer-to-peer trading in environmental commodities, renewable energy, and raw materials, to offset emissions and enhance renewable energy uptake (e.g. Power Ledger), and to increase efficiency and transparency between producers of raw materials and intermediary goods (e.g. Raw Coin), respectively.
	Limited knowledge to facilitate collaborative consumption: lack of data on market demand and supply for shared goods and services, lack of knowledge about consumer preferences / behaviour.	IoT, blockchain, online platform	— *Tracking and sharing of industrial equipment* enabled through online platform and NFC/QR identifiers and/or GPS trackers, for digital sharing and tracking of machines, devices and other goods (e.g. eRENT).
		Online platforms, AI, machine learning, big data, cloud computing, blockchain	– Sharing economy based on *shared use of assets* and integrated pay-as-you-go-fares, enabled through personalised customer experience, setting smart prices, preventing fraud, automation, and improving internal operations (e.g. Uber and Blablacar for mobility on demand and carpooling, Airbnb for space sharing, Peerby for household items sharing).
	Limited knowledge to facilitate collaborative production: lack of access to data / information on state of products, manufacturing resources and equipment conditions, and manufacturing processes.	Cloud computing, IoT, big data, online platform	– Cloud computing utilising virtualisation to encapsulate *collaborative design and manufacturing resources as services*, thereby allowing for resource sharing and cooperative work between producers across the value chain (e.g. cloud-based design and manufacturing combining infrastructure as a service (IaaS) – Amazon Elastic Compute Cloud, platform as a service (PaaS) – Google BigQuery, software-as-a-service (SaaS) – Dassault Systems, and hardware as a service (HaaS) - Quickparts.com).
	Limited data on location, condition, availability of products, services, equipment; lack of information about product / service uses; lack of knowledge about consumer preferences / behaviour.	IoT, online platform, cloud integration, (machine learning)	– Connected assets can now also be *sold by the hour or year,* or *as-a-service*, saving capital costs and ensuring more effective use of resources throughout their lifecycle (e.g. water pump by the hour, compressed air as a service - Kaeser Kompressoren, light as a service – Philips, OSRAM). – *Cloud enabled infrastructure* can substantially save costs, energy and materials otherwise needed to produce assets physically (e.g. Netflix, Spotify, Coursera).

MARKET INEFFICIENCIES	DATA, INFORMATION, KNOWLEDGE MISSING	ENABLING DIGITAL TECHNOLOGIES	EXAMPLES OF CIRCULAR ACTIVITIES
CONSUMPTION EXTERNALITIES	Lack of data on quality and supply of recycled materials, condition and availability of second-hand products, and lack of consumer's awareness about their (re)use.	IoT, big data	– *Digitally validated quality control system* through end-to-end tracking of the material flow (using sensors and data analytics), which allows improving quality of secondary raw materials and increasing their reuse (e.g. Di-Plast technology under development within packaging and building B2B-supply chains).
		Online platform, AI and machine learning	– *Automated grading solution* to improve the current visual and mechanical inspection and cosmetic assessment of electronic devices (e.g. Teleplan Optiline). – *E-commerce platforms* for refurbished consumer electronics (e.g. Refurbed), and car parts (e.g. GPA Recycleur d'Automobiles), as well as retreaded and regrooved tyres (e.g. online retreaded tyre selector by Michelin).
TECHNOLOGY EXTERNALITIES (AND IMPERFECT INFORMATION)	Lack of information on composition, durability, modularity, and subsequent disassembly and recyclability of materials, components and parts, for collaborative and circular design.	Computer software, online platform, 3D printing	– *Computer aided design (CAD)* to assist in the creation, manipulation, analysis, or optimisation of a design in 3D printing, and *building information modelling (BIM)* to ensure that appropriate information is created in a suitable format at the right time to help improve infrastructure design and increase collaboration across all stages of the construction project (e.g. Geomagic Design X by 3D Systems, Autodesk BIM 360).
	Insufficient information about the composition of waste streams and missing dismantling instructions.	AI and robotics (incl. machine vision), sensors	– *AI enabled technology equipped with machine vision* used to analyse and sort material streams (e.g. Max-AI technology used by BHS Bulk Handling Systems for sorting municipal waste, TOMRA Sharp Eye technology with near-infrared (NIR) scan system which enables 3D optical sensing for separating single-layer PET trays from PET bottles). Robots detecting parts within iPhones and stripping them out safely and efficiently so they can be refurbished, as well as recovering valuable materials (e.g. Liam and Daisy by Apple). Robotic recycling system designed to reclaim raw materials from construction and demolition waste (e.g. ZenRobotics Recycle by Suez and ZenRobotics).
		AI and machine learning, IoT, big data, (blockchain)	– *AI-powered bin* that aims to cut down on food waste, using cameras, smart scales, and machine learning to keep track of types of food thrown away too often, helping restaurants to save money, and the environment (e.g. Winnow Vision). Waste collection based on a collaboration platform to reward plastic waste sorting by individuals and companies (e.g. YOYO).

Note: Note that the table is not intended to provide an exhaustive overview, rather a careful selection of examples to illustrate the extent to which digital transformation facilitates specific circular activities, by addressing respective market inefficiencies through data, information and knowledge generation. Note also that the latter may contribute to solving more than one market inefficiency (e.g. the overlap between imperfect information and consumption externalities, and between imperfect information and technology externalities). Finally, note how technologies often interact to deliver a digital circular solution.

Source: Own elaboration.

4

The role of digital technologies in supporting the effective delivery of circular economy policies

Besides fuelling circular activities in the private sector, digital innovation, data and uptake of digital solutions can also be leveraged by policy-makers to create greater efficiencies, improve sustainability and drive economic development.

The profound impact of digital transformation in the private sector has not been mirrored by equally significant adoption in the public sector so far. Yet, some evidence has been identified on application of digital technologies for reshaping existing policies, enabling innovative policy design and rigorous impact evaluation, and expanding citizen interaction and stakeholder engagement in policymaking (OECD, 2019[64]). Data-driven approaches to governments' foresight capacities to better anticipate societal trends and needs, can lead to efficiencies and more target-specific policymaking. However, the extent to which digital transformation will help to improve policy making will depend on governments' willingness and ability to scale digitalisation (in making public infrastructure available to link disparate sources of data and its interoperability) and to address privacy concerns and digital security vulnerabilities (driven by elevated granularity of data, increased data sharing across government agencies and public private partnerships) (OECD, 2019[64]).

The OECD has produced extensive work related to this topic, including recommendations for digital government strategies and a suite of country studies (Digital Government Reviews), which provide a wide range of examples on how digitalisation can transform the public sector (OECD, 2018[65]). The following sections discuss how digital technologies can support the effective delivery of circular economy policies.

4.1. Policy data and analysis

Access to unprecedented volumes of crowdsourced and online data, which was previously unobservable or was only observable and collected at a prohibitive cost, enables policymakers to better understand and manage resources and waste, to reduce urban pollution and to rethink urban transportation (Veolia, 2017[66]). Big data collected through digitalisation enables policymakers to identify priority areas and to make data-driven policy decisions.

An example of digitalisation contributing to *more informed policy priorities identification* is the Marine LitterWatch mobile application developed by the European Environment Agency. The combination of a mobile app, online platform and public database, allows collecting data on marine litter on beaches and other stretches of coast reported by citizen communities. This information is then used to strengthen and share the knowledge base on marine litter and ultimately facilitates the development of measures to tackle the waste stream (European Environment Agency, 2015[67]). On a larger scale, the Horizon 2020 funded CLAIM project aims at cleaning marine litter by developing and applying innovative methods, with a specific focus on the Mediterranean and the Baltic seas. One of the core areas of the project is to collect samples and generate datasets on invisible and visible plastic litter, which would drive the development of modelling tools to identify pathways and accumulation areas of marine litter and support policymaking (CLAIM Project, 2018[68]).

In terms of data-driven policy decisions, *predictive data analytics and anticipatory decision making* powered by machine learning and AI, is to be used for air emissions regulation and monitoring of water quality by the US Environmental Protection Agency (Siegel, 2018[69]). Similarly, the European Environmental Agency offers a database of interactive maps for data visualisation, among others on air quality, fragmentation pressure on urban and transport infrastructure expansion, noise pollution, green infrastructure indicators and various water quality indicators (European Environment Agency, 2019[70]; Francart and Höjer, 2019[71]). Additionally, geo-referenced and crowdsourced data collected through remote sensing and geographic information systems (GIS) techniques, coupled with data from social networks, mobile phones and credit card transactions, can be used for complex modelling at the city level (also called *urban modelling*). Assessing natural resources and monitoring spatial changes might allow better urban planning in terms of design and zoning and ultimately lead to a more efficient allocation of resources (such as urban growth and sprawl, which in practice translate into physical transformation of urban land into buildings and infrastructure) (Ngie et al., 2013[72]).

On the level of specific supply chains, the European Platform on Lifecycle Assessment provides an online platform collecting large datasets to enable *policy-oriented environmental assessments*. This can, for instance, be used to drive life cycle thinking in the implementation of the EU's thematic strategy on prevention and recycling of waste, or in eco-design criteria setting (European Commission, 2019[73]).

Yet another example might be drawn from the Dutch Rijkswaterstaat agency, which is currently working on a *data strategy for circular economy* (see Box 4.1). DigiDeal for the built environment is a sector-wide agreement about exchange, ownership and organisation of data and information in the construction industry. Through agreed standards, this should facilitate the smooth exchange of existing data across all stakeholders (including the Government) and thereby help developing smart and innovative solutions across the construction sector in the Netherlands (Rijkswaterstaat, 2019[74]).

Box 4.1. The Dutch infrastructure digital approach to circular economy

The Government-wide programme for a Circular Economy aims at realising a fully circular economy in the Netherlands by 2050. The ambition is to realise, together with a variety of stakeholders, an (interim) objective of a 50% reduction in the use of primary raw materials by 2030 (Dutch Ministry of Infrastructure and the Environment, 2016[75]).

Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management, and is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands (Rijkswaterstaat, 2020[76]). Maintaining over 6000 assets like bridges, sluices, viaducts, aqueducts, and over 3000 km national road infrastructure, cannot in practice be achieved without having access to detailed information about all these assets. Notably, data and information on how assets perform, which materials / components they are made of, how the individual elements are connected, and which repair and maintenance have they undergone during their life time, are crucial for the potential future re-use of embedded materials. While in the past such informational aspect has not been taken into account, nowadays Rijkswaterstaat has an explicit ambition of becoming a data driven organisation (Rijkswaterstaat, 2018[77]).

Rijkswaterstaat has therefore started exploring the first strategy steps towards a digital circular construction sector. In order to create a consensus on the concept of a Circular Building sector, Rijkswatersaat has established a public private discussion platform together with the National real estate company and the National Standardisation body (PLATFORM CB’23, 2020[78]). Over hundred stakeholders have been engaged in discussions on how to measure circularity and what type of information material passports standards need to contain, to achieve the goals. The guides 'Core method for measuring circularity in the construction sector' and 'Passports for the construction sector' have been drawn up. How this information and data exchange should be organised in practice is currently under debate among the coalition aiming to professionalise the digital construction sector (DigiDealGO, 2020[79]).

Rijkswaterstaat has also participated in other data-driven initiatives, such as the piloting of a Dutch start-up Excess Materials Exchange (Excess Materials Exchange, 2019[43]) (aiming to develop a cross sectoral ‘dating site for secondary materials’ based on blockchain technology), and exploring a possible role of the Dutch start-up Madaster in the infrastructure sector (aiming to become a central register of materials use in the construction sector) (Madaster Foundation, 2020[80]).

4.2. Policy design and reshaped government-citizen interaction

Digitalisation brings new instruments for governments to experiment with more effective design and evaluation of policies (OECD, 2019[64]). For instance in transport, big data and IoT support policymakers in *designing innovative policies* (such as road pricing based on times and distances travelled) and flat congestion charges. Similar to congestion tariffs (which are based on the producer-pays-principle, and thereby contribute to managing congestions as well as to behavioural change), cities could use intelligent assets to develop incentive schemes to become more resource efficient, such as the pay-as-you-throw system in municipal waste management (Ellen MacArthur Foundation, 2016[7]). As illustrated by the *volume-based waste charging system* which has been in place in Korea since 1995 (UN ESCAP, 2012[81]), introducing volumetric tariffs for waste lead to increases in recyclability and improvements in waste disposal behaviour. For instance, in Seoul the food waste is measured applying an RFID-based weighing system (which allows authorities to monitor the weight of waste disposed and to impose fees accordingly), or RFID chips and stickers used with standard containers (which enable disposable or monthly volume measuring). Such systems rely on the combination of devices for weight measuring, chip recognition and volume tracking and storage. Another example of digitally-enhanced municipal waste management is *smart waste collection* enabled by IoT and sensors (possibly also accompanied by radio frequency mesh and Wi-Fi), which helps increasing efficiency and improving quality of waste collection services (Jung, 2017[82]) (see Box 4.2).

Box 4.2. Smart waste management across municipalities in Slovakia and the Czech Republic

Several cities have already implemented smart management waste solutions. In case of the capital of Czech Republic, the intelligent waste management has been introduced within its zero waste plan of the Smart Prague 2030 (Smart Prague, 2019[83]). Another example is the city of Nitra in Slovakia, which has decided to combine the introduction of new large capacity bins with introducing waste efficiency measures (NKS, 2017[84]). Many other cities around the world that introduced digitally-enhanced waste management solutions have been benefiting from optimised waste management, reduced costs, improved environment and quality of services, and better quality of citizen life.

More specifically, fitting (semi-)underground containers and regular bins with technology using ultrasonic IoT fill-level smart sensors, allows real-time monitoring of waste levels across individual cities. The data collected is subsequently processed and stored on a cloud-based platform, through which municipalities can identify all the bins on a digital map (including their capacity, waste type, last measurement, GPS location and collection schedule or pick recognition) (SENSONEO, 2019[85]). Such smart analytics enables municipalities to make data-driven decisions with regards to optimising waste collection routes, collection frequencies, and vehicle loads (minimising thereby the impact of waste collection on traffic, its environmental footprint and costs, and also allowing to assure sufficient free capacity of bins at all times). Analytics also allow building a bin inventory, determining waste production across individual parts of the city (in terms of its quantity, timing, and type), and recording maintenance evidence of waste bins. This in turns improves the planning for capacity and bin allocation across the city. Additionally, a compatible mobile application may help citizens conveniently locate the nearby empty containers, provide feedback on any overflowing bins, or request free cans (SeeClickFix, 2015[86]; SENSONEO, 2019[85]).

In terms of government-citizen interaction, digitalisation helps fostering positive relationships with citizens and businesses. On the one hand, the fact that governments are making more online data freely available enhances accountability of the public sector and facilitates *civil society oversight on compliance efforts and breaches* (OECD, 2019[64]). This contributes to increasing the sustainability of public resource use (including natural resources). On the other hand, the improved availability and accessibility of environmental information (such as state of environment, environmental permits and natural resource use) allows raising awareness and empowering stakeholders. In Estonia, Slovakia and Czech Republic (as well as in many other countries) online platforms have enabled more transparent and efficient civic engagement through digital public consultations of environmental strategies. Developing *citizen-driven policies and services* requires extensive engagement with citizens to understand their perspectives, opinions and needs. Digital platforms in combination with AI and machine learning algorithms (used to better analyse the citizen input, to cluster similar contributions by theme, trait or location, to identify citizen's priorities and to generate reports with policy recommendations) enable civil servants to tap into collective intelligence and make better-informed decisions and to improve government's responsiveness (Berryhill et al., 2019[87]). An example of such *citizen participation platform* is the Belgium's CitizenLab, which has been used to crowdsource policy priorities in waste management for the city of Liège (Liège, 2020[88]). Other examples are mobile applications (such as SeeClickFix, and StreetBump) that allow citizens to report various urban conditions directly to city halls (such as potholes on roads, stray garbage and maintenance of waste stations) (OECD, 2017[1]).

4.3. Improved implementation

Increased possibility to monitor outcomes directly through availability of data and information enables more effective enforcement and targeting of existing policies (OECD, 2019[64]). For example, machine learning and AI can be used for detecting fraudulent behaviours and ensuring compliance in innovative ways. The Swedish Energy Agency uses Nordcrawl (a *software platform for monitoring, verification and enforcement* based on near real-time web crawler data) to collect and analyse data from websites of household appliance retailers. Such data provides enhanced knowledge for more effective market surveillance (enabling compliance checking against energy class, eco-design and labelling regulations) and informs policy development (by helping to identify market trends, such as instance growing sectors, or inappropriate technologies) (Swedish Energy Agency, 2019[89]). Another example is the *online system to help tracking and reporting hazardous waste shipments* for better compliance monitoring established by US Environmental Protection Agency (see Box 4.3).

Box 4.3. US EPA's Hazardous Waste Electronic Manifest System (e-Manifest)

The US EPA has established a national system for tracking hazardous waste shipments electronically. Launched on June 30th, 2018, this system, known as "e-Manifest," is set up to replace a decades-old paper intensive tracking system that relied on carbon-copy paper manifests (up to 6 copies per manifest) that had to be shipped alongside the hazardous waste material it tracks (US EPA, 2019[90]).

The new e-Manifest system serves as a one-stop electronic hub for digital manifests, and features a simplified manifest submission process, more accurate and timely information on waste shipments, rapid notifications on waste discrepancies, as well as increased effectiveness of compliance monitoring of waste shipments by regulators. Additionally, the manifest reporting could inform the Resource Conservation and Recovery Act biennial reporting process, for improved control of hazardous waste within its sustainable materials management (SMM) program.

The costs of developing and operating the new e-Manifest system (development, operation, maintenance and future upgrades), are to be recovered from user fees charged to those who use hazardous waste manifests to track off-site shipments of their wastes (i.e. according to whether manifests are submitted electronically or via paper, reflecting the varying processing costs of these options, fees range from USD 5 - 15 per manifest and are paid for by the user).

The modernisation of the national system spans hazardous waste tracking from the point of generation, its subsequent transport to a destination facility, and its end use as either treated, stored or disposed of waste (i.e. cradle-to-grave). By enabling the transition from a paper-intensive process to an electronic system, the EPA estimates e-Manifest will ultimately reduce the burden associated with preparing shipping manifests by between 300,000 and 700,000 hours, saving state and industry users USD 75 – 90 million annually.

Yet another digital solution helping to improve the circular economy policy implementation and waste prevention has been identified in the area of environmental crime. Losses from waste trafficking (in form of hazardous waste and electronic waste being smuggled through customs as second-hand product or using non-hazardous waste codes) have been estimated to amount to USD 10-12 billion annually (Nellemann et al., 2016[91]). The debate on enforcement and compliance with waste regulation has gained attention on both domestic and international policy agendas. One example of a policy enforcement initiative is the UK's project on introducing monitoring and clamping down on illegal movements of waste. As a response to tax avoidance and illegal exports through mislabelled waste, the UK Government is exploring the possibility of introducing *compulsory electronic tracking of waste* (UK DEFRA, 2019[92]) (see Box 4.4).

The above examples are just a few of the digital solution applications currently leveraged by policy-makers to create greater resource efficiencies and improve sustainability. There are more such applications currently under development, pointing to the importance of data and information generated through digital transformation in circular economy and resource efficiency policy making. A more comprehensive overview will require an in-depth analysis of current and planned initiatives across countries.

Box 4.4. UK GovTech Catalyst Challenge: Smart Waste Tracking

The UK Government is working with industry on the development of an electronic waste tracking system for business to record all waste movements through the economy. The purpose of this work is to improve the quality and accuracy of waste data, and make it more accessible and useable by businesses, regulators and government.

Giving access to information on the UK's 200 Mt of waste will help businesses drive up their productivity and competitiveness. Facilitating the use of waste resources at their highest value reuse opportunity is a central goal of our Resources and Waste Strategy as well as supporting the shared goals of our modern Industrial Strategy, Clean Growth Strategy and 25 year Environment Plan.

Currently the UK has no single or comprehensive way of tracking waste, and many businesses do not have the information they need to unlock the potential value of waste materials in order to reduce raw materials costs and develop new revenue streams.

An innovative digital solution that captures better data could help identifying how to maximise the value extracted from waste, support secondary material markets and boost productivity. It could also provide a basis for more effective compliance and enforcement work, so reducing waste crime by amongst other things detecting:

- Waste that disappears or doesn't reach next stage of the chain (illegal dumping);
- Waste descriptions that change when they shouldn't (landfill tax avoidance);
- Unusual patterns of waste transfers (indicating potential fraud schemes); and
- Relationships across waste chains (aiding mapping of serious organised crime groups).

To establish the potential for waste tracking the UK has used the Government's GovTech fund, to finance tech firms' innovative solutions to waste tracking. Five companies have been awarded up to £80,000 to develop innovative digital solutions to record and track individual movements of waste through the economy (how waste is generated, handled, and disposed of). At the end of a three month feasibility stage, up to two projects will be funded up to £500,000 each to develop and field test a prototype (UK DEFRA, 2019[92]).

The feasibility projects include research into tracking waste through electronic chips and sensors, the use of blockchain, looking at an open data standard, as well as new data analytics and the use of artificial intelligence, to help users decide what to do with the waste they produce.

Running in parallel, the UK also conducted user research to better understand the requirements of businesses, local authorities, regulators and government. This information will help inform the functionality of a waste tracking service as the UK moves from feasibility projects towards development of a prototype service that could significantly benefit waste and resources management, and bring about real change.

By helping the regulators take action against waste crime, and identify opportunities for companies to join up their waste operations, the project will help to maximise the value of waste as a resource (and thereby boost the emerging industry of circular waste management), and at the same time minimise damage to the environment (cracking down on waste criminals, and help achieving zero avoidable waste in the UK by 2050) (UK DEFRA, 2019[92]).

5

Unintended consequences of digitalisation of the circular economy

While digitalisation of circular economy can lead to many positive transformations, some potential negative consequences could result from a broader uptake of both digital technologies and circular business models. As critical infrastructure becomes increasingly dependent on digital technologies (driven by increased collection, processing and use of data points) and data use, security, privacy, ownership and transparency, the negative implications of digitalisation has become more obvious. For instance, identification of who the liability lies with when a problem in an online transaction occurs, or who owns and manages the data collected and controls the intellectual property rights (IPRs) when an interconnected device transmits incorrect data or fake measurements, have been identified as key issues for consumer protection related to online platforms and IoT (OECD, 2016[93]; Brous and Janssen, 2015[94]; OECD, 2016[11]). Similarly, when collecting data for national security interests through big data analytics, governments are facing privacy protection challenges to personal data being shared across various governmental agencies (OECD, 2017[1]). Additionally, data breaches (weather caused by malicious activities or accidental losses) and identity thefts, can harm individuals and carry significant financial consequences and reputational losses for businesses. On the corporate level, one of the main downsides of using cloud computing is the potential threat of disruption of cybersecurity models when migrating data and processes to public clouds (McKinsey, 2018[95]). The risks of cyber intrusion and industrial espionage are the most eminent for components of IoT, which are prone to becoming targets of digital security incidents (OECD, 2017[1]).

Besides the generic risks associated with the use of digital technologies, there are also more specific risks directly related to the use of resources. With regard to scalability of technologies, blockchain and AI are expected to drive the demand for data centre services exponentially, requiring larger computational power, storage and bandwidth in the future (OECD, 2017[1]). Data centres and data transmission networks are emerging as an important source of energy and material demand (Francart and Höjer, 2019[71]; OECD, 2018[96]). Considering the case of blockchain uses for cryptocurrencies, the Bitcoin's current annual electricity usage estimate is between 46 and 74 terawatt-hours (an estimated increase of 800% since 2017). The resulting environmental impact amounts to annualised carbon footprint in the range of 22 to 35Mt of CO2 and electronic waste of 11kt (Cambridge Centre for Alternative Finance, 2019[97]; Digiconomist, 2019[98]; Stoll, Klaaßen and Gallersdörfer, 2019[99]).[8] However, it is to be noted that most of the environmental arguments against blockchain uses are closely linked to the computation-heavy cryptographic operations for Bitcoin mining. Other blockchain based technologies (such as those discussed in this paper) might also require fair amounts of computational energy, yet they are substantially less wasteful (Stoll, Klaaßen and Gallersdörfer, 2019[99]; Manganello, 2019[100]).

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[8] These levels are comparable to power consumption of Austria, carbon footprint of Denmark and e-waste generation of Luxembourg (Digiconomist, 2019[98]).

Similarly, the wider adoption of 3D printing brings with itself negative environmental implications both in terms of significant energy consumption (for heating and cooling, and due to employing low-efficacy types of material deposition such as laser sources) and raw material losses (degradation and wastage) (Baumers et al., 2017[101]). In terms of the material uses, there seems to be uncertainty about the potential to recycle waste material and printed parts, due to potential changes in material properties post-printing and the pigments that may interfere with plastic separation processes (McAlister and Wood, 2014[102]). Moreover, although currently most of the 3D printers are limited to producing objects compiled of a small number of distinct materials, production of more complex plastic products might exacerbate the issue of recyclability, due to the layering different polymers (Pearson, 2018[103]). Last but not least, as a result of plastics being heated to high temperatures, 3D printers are high emitters of ultra-fine particles and potentially toxic by-products (McAlister and Wood, 2014[102]). On another level, raw materials used for manufacturing of 3D printers, along with the increased risks of counterfeiting and patent violations from 3D printing, represent another set of unintended consequences for this type of manufacturing.

The unintended consequences of the digital circular economy, in terms of environmental, economic, social, and regulatory challenges are discussed below.

5.1. Environmental

Whereas environmental benefits of circular economy are often taken for granted, potential unintended consequences that might counteract some of the benefits of the transition are rarely discussed. These range from physical and economic limits of recycling activities to environmental desirability of reused products to rebound effects (Makov and Font Vivanco, 2018[104]). The latter have a strong parallel to energy efficiency rebound, whereby the increased in-use phase efficiency of a product (i.e. technological change) is partly or completely offset by its increased overall use (i.e. behavioural response). By analogy, in circular economy, rebound effects translate into increased levels of production and consumption, which offset increases in production and consumption efficiencies (Zink and Geyer, 2017[105]).

There are two types of mechanisms that could lead to a rebound in the circular economy: *direct* and *indirect*. The direct rebound effect describes the case where efficiency improvements of using a certain material reduce the unitary cost of the final product / service it provides. This in turn triggers an increased demand for the material, offsetting thereby some of the initial savings. The indirect rebound effect refers to the additional offset, driven by the increased available income from the material efficiency improvement. This can lead to additional increase in demand for other products / services, which further increase the demand for the material in question (Freire-González and Font Vivanco, 2017[106]; OECD, 2019[3]). For example, the use of more efficient household appliances and refurbished electronics could result in monetary savings, which consumers might spend on purchasing more electronic appliances (thereby exercising pressure on materials and waste management)[9], or on increasing the demand for some other energy / material intensive services, such as cloud computing. The increased consumption of products / services in both cases is driven by a perceived increase in wealth. Therefore the two effects are jointly referred to as *income effect*.

The *substitution effect* instead, causes consumption choices to change further to the relatively lower price of the product / service (i.e. a product becomes relatively more attractive, on top of the income effect) (Zink

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[9] A record 53.6 million metric tonnes (Mt) of electronic waste was generated worldwide in 2019, representing a 21% increase in just five years (United Nations University, 2020[156]).

and Geyer, 2017[105]). Such relatively lower prices allow new consumers to enter the market, and thereby increase the demand for cheaper recycled materials or cheaper refurbished products further.[10]

Examples of rebound effect in other industries include transportation, housing and extractives. In transportation, an increased demand for mobility on demand (e.g. Uber) at the expense of public transport would trigger an increase in the demand for energy and materials. In housing, sharing business models (e.g. Airbnb) might cause housing in city centres to be predominantly used for temporary rentals, forcing local population to move outside of the city centres. This might drive urban sprawl (possibly further exacerbated by deployment of autonomous vehicles), which in turn would increase the environmental footprint due to distances travelled and new housing built.

Finally, just as digital technologies can help improving efficiency in circular economy, they also push linear growth and consumption. In the extractives, the most frequently leveraged digital technologies (including robotics / automation, remote operating centres, wearable technology and real-time analytics and visualisation) are predicted to help the industry generate a profit of USD 190 billion within a decade (Callahan and Long, 2017[107]). These technologies are mainly embraced in mine operations, but also facility exploration and mine development. For instance, when deployed in the oil and gas sector, smarter management of complex systems algorithms by AI makes it easier to find oil and gas sources and to manage production. This helps boosting productivity and keeps fossil energy plentiful. Cheap energy from fossil fuels makes it harder to achieve emission cuts targeted within the scope of the Paris Agreement (Victor and Yanosek, 2017[108]).

5.2. Social

The threat of disruption to the current employment landscape is perceived as one of the most pronounced social risks of digitalisation of the economy. Changes to business models driven by digitalisation are expected to profoundly impact employment, in terms of both job creation and job displacement, as well as heightened labour productivity and widening skills gap. According to the World Economic Forum estimates (2016[109]) the net employment impact for the period 2015-2020 would be 5.1 million jobs lost to disruptive labour market changes. Among the main technological drivers identified are[11]: mobile internet and cloud technology, processing power and big data, new energy supplies and technologies, as well as IoT, sharing economy and peer-to-peer platforms, robotics and autonomous transport, AI and machine learning, and 3D printing.

At the sectoral level, the most affected sectors are projected to be transportation, manufacturing, agriculture and services (PwC, 2018[110]). On a more global scale, research by McKinsey shows that intelligent agents and robots could eliminate nearly a third of the world's human labour, displacing between 400 and 800 million jobs by 2030 and forcing up to 375 million people to switch job categories and learn new skills (Chui, Manyika and Miremadi, 2015[111]).

On the aggregate level, only AI and to some extent 3D printing are forecasted to have negative impacts on employment (contrasted with job creation potential of big data analytics, mobile internet and cloud technology, and IoT). However, when disaggregated to job families, the impact of digitalisation might vary. For instance, labour-substituting technologies, such as additive manufacturing and 3D printing, have

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[10] Additionally, the reuse of repaired or refurbished pre-owned products might lock customers into less efficient alternatives, by preventing them from benefitting from technological improvements incorporated within newer models (Makov and Font Vivanco, 2018[151]).

[11] Besides technological drivers, the main demographic and socio-economic disruptions to industries and business models are: changing nature of work and flexible work, rise of middle class in emerging markets, and climate change and natural resources.

negative employment effect in manufacturing and production, whereas they are drivers of employment creation within architecture and engineering (along with robotics and autonomous transport). Similarly, while processing power and big data, IoT, mobile internet and cloud technology are driving both employment growth for computer and mathematical roles and job displacement for office and administration, and installation and maintenance (World Economic Forum, 2016[109]).[12] Ultimately, the assessment of the overall effect of how job destruction and creation play out in the context of digitalisation and circular economy will require macroeconomic modelling.

5.3. Economic

The use of digital technologies for the circular economy have been shown to drive value creation for businesses, as well as to increase traceability and trust on the market (OECD, 2018[112]). However, digitalisation might also trigger market distortions, such as market concentration. For instance, small and medium sized enterprises (SMEs) and start-ups might not be fully aware of the opportunities offered by existing software and hardware solutions. They might therefore have more restricted access to emergent technologies, compared to large players. They might also be facing more difficulties in accessing and using data, information and knowledge generated by these technologies. This might further exacerbate the barriers to entry on the market and difficulties in scaling up operations, making it more difficult for them to compete against large incumbents (Climate-KIC, 2018[12]; OECD, 2015[113]). The latter, in turn, could further deteriorate competition in some markets that are relevant to circular economy, such as waste management (parts of which are regularly raising concerns about competition) (OECD, 2016[114]; OECD, 2013[115]). However, the opposite may hold true for digital competition in the waste collection industry. The late adoption of digitalisation by established companies might give ways to start-ups that are disrupting the traditional waste management business models (AMCS Group, 2016[116]).[13]

5.4. Regulatory

The fast expansion of new business models, especially the sharing economy, has also led to some recent and unexpected regulatory intervention. A growing number of countries and local communities have become increasingly concerned about the negative side effects of the expansion and started to implement measures to slow the growth of certain sharing business models (mainly those of ride hailing and temporary lodging platforms). At the core, these measures are aimed at protecting users and citizens, more specifically improving safety through driver registration, reducing the influx of travellers into quiet residential neighbourhoods, or preserving jobs of the "traditional" service providers (such as taxi drivers and hotel employees). Some of the examples of such regulatory interventions are the rulings against Uber in Denmark, Hungary and Bulgaria, the crackdowns on short-term rentals in Paris and the removal of listings without licences from online platforms in Barcelona (Thiha Tun, 2019[117]; Hao, 2017[118]). Another example is the national guideline governing bike sharing schemes issued by the Chinese Central Government,

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[12] Augmented by socio-economic and demographic drivers.

[13] One example of such game changer is the on-demand waste collection introduced by Rubicon Global. While not owning a single vehicle or container, its business model is based on an online platform and mobile application enabling a digital marketplace through which the "Uber-like" on-demand waste collection is managed. Additionally, it provides data analysis for both government and businesses, as well as other cloud-based waste and recycling solutions (Rubicon Global, 2019[153]).

which mandates municipalities to cut their excessive supply (in response to the clogged pavements and entrances to underground stations by deposited shared bicycles) (Hu, 2017[119]).[14]

Digitalisation may also lead to weakening existing regulation. For example, the expanding use of international market places may induce free-riding of online retailers on extended producer responsibility (EPR) schemes. Under such schemes, manufacturers and retailers selling their products on international marketplaces are required to register with administrative authorities and contribute financially to the costs of local and national waste management schemes. Around 400 EPR schemes are currently in operation across the OECD countries, with majority covering electronic and electrical equipment (EEE), packaging, tyres, or batteries.[15] According to estimates, EPR fees are currently unpaid for up to 10% of the value of the EEE on digital marketplaces across the OECD countries (Hilton et al., 2019[120]).

At the same time, lagging regulation may inhibit online sale of parts (for example used for repair of EEE and vehicles) and refurbished products. Although their volumes have been growing in the past years[16], the currently missing legislation on “right to repair” inhibits consumers repairing and modifying their electronic devices and obliges them to use services and parts provided by authorised vendors or original equipment manufacturers (OEMs) only. The Motor Vehicle Owners' Right to Repair Act in the US and the recent inclusion of reparability requirements for washing machines, dishwashers, refrigerators, televisions and lighting within the EU's Ecodesign Framework[17] are examples of such nascent legislation (Industry Europe, 2019[121]). Similarly, the online sale of refurbished products is hampered by lack of clear definition of what refurbished products stand for (ECC Belgium, 2018[122]). The lack of awareness and misunderstanding of what refurbishment entails, as well as the negative trade-off between perceived risks and benefits, have been established as the key barriers of consumer acceptance to refurbished mobile phones (van Weelden, Mugge and Bakker, 2016[123]).

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[14] For instance, in Shanghai alone the number of shared bikes in circulation was the double of the optimal number estimated (Hu, 2017[119]).

[15] A professional seller on eBay is estimated to reach on average more than 20 different markets each year, with 1 out of 5 products that were pre-owned (eBay, 2019[159]).

[16] For instance, the volume of refurbished products sold on eBay in Germany and France has increased by 80% and nearly 500%, respectively (eBay, 2019[154]; eBay, 2019[155]).

[17] Note that the right to repair as defined within the Directive only extends to professionals carrying out the repairs, not consumers themselves. Altogether excluded from right to repair are smart phones and laptops (Industry Europe, 2019[121]).

6 Digital circular economy and policy implications

Digitalisation helps to address some important market failures that stand in the way to transitioning towards a resource efficient and circular economy. Digital transformation, and the data, information and knowledge it helps generating, improve the business case for existing circular economy activities and enable the development of new circular business models. However, in order to realise this potential, an enabling policy framework that promotes the digitally enabled circular activities while mitigating the risks that these bring with them, will need to be established. Some of the key elements of such policy framework are:

Addressing the systemic risks of digital technologies that may otherwise stand in the way of their wider adoption in the market. Challenges around data security, ownership and privacy, need to be addressed through policies for better data governance and access to data. Such policies should aim at addressing digital security, balancing privacy with openness, and promoting better measuring and valuing of data.

Supporting the development of circular economy relevant digital applications through R&D policies and programmes to speed-up the transformation. A more open-source multi-stakeholder collaborative R&D needs to be encouraged to foster innovation in circular business models enabled by digital technologies. Aside from incentivising private investment through economic instruments (such as tax reliefs, exemptions, cross-border EPR systems), public funds could be focused on funding initial phases of R&D, complemented with blended-finance models (jointly with the private sector), and supported by green public procurement targeting innovative circular activities and relevant digital applications. Investment into shared data infrastructure might contribute to scaling new business models further.

Supporting the development of standards and harmonised data protocols that are crucial for the use of digital technologies in the circular economy. Lack of access to and ownership of data (and its sharing across private and public owners), along with lack of data standards and interoperability of datasets, slows down the uptake of digital technologies in general, and the scalability of digital circular business models in particular. In terms of standardisation, public data across countries (for instance on recycling) might be difficult to collect and process, because of the lack of centralisation (in terms of collection and dissemination methodologies). Therefore, encouraging open-source interoperability of data and globally distributed data architecture would help ensuring access to large sets of data records and computing infrastructure.

Addressing the risks linked to unintended consequences of the digital circular economy scale-up. To mitigate the unintended consequences of the increased uses of digital technologies, policies should focus on integrating circularity aspects into digitalisation, addressing material and energy efficiency in their design. To alleviate potential environmental rebound effects, policies should aim at encouraging green design and improving social perception of pre-owned or recycled products. In response to concerns about labour market transition triggered by digital circular economy disruptions, training workforce with future proof skills and developing new approaches to basic and lifelong education, as well as regulating new working arrangements will become essential. With regard to regulation, flexibility in regulatory approaches will be required in order to balance competing considerations of consumer protection with too much regulation (which might halt disruptive innovation and thereby reduce the actual benefits to the consumers). Furthermore, developing voluntary e-commerce codes of practice and a harmonised framework of EPR registration for online retailers across jurisdictions could address free-riding on digital market places. Finally, introducing legislation on “right to repair” and clarifying the definition of what a refurbished product stands for, will contribute to removing impediments to repair and refurbishing, eliminating perceived risks and increasing consumer acceptance, and ultimately ramping up online sales of such products and parts.

Encouraging circular economy policy making using digital technologies and the data they generate. Besides playing a crucial role in circular business models, digital innovation and the uptake of digital solutions may also help improving circular economy policy making. In order to transpose this link into practice, governments should consider exploring data-driven approaches to their foresight capacities in order to better anticipate environmental and societal trends and needs, and as such to increase efficiencies and better target circular economy policy making.

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Annex A. Digital Technologies

Internet of Things

The Internet of Things (IoT) is the inter-networking of physical devices and objects, whose state can be altered via the internet, with or without the active involvement of individuals (OECD, 2015[124]). IoT includes sensors that gather data and exchange them with one another and / or with humans. The main value driver of IoT is the capability to define location, condition and availability of the assets they monitor. It is estimated that by 2020 at least 20 billion devices are connected to the IoT worldwide (Gartner, 2017[125]). The networked sensors in the IoT and the data they collect can, for instance, be used to monitor health, location and activities of people, the state of production processes, or the efficiency of city services and of natural environment (OECD, 2016[126]). Underpinned by trends in big data analytics, cloud computing and machine learning (which allow compiling, linking and analysing large data sets in real time), the IoT technologies can empower intelligent systems and autonomous machines (OECD, 2015[113]).

The IoT enables new business models, applications and services based on data collected from devices and objects (OECD, 2018[127]). It may also facilitate the adoption of applications that are favourable to circular economy. For instance, by automatically and remotely monitoring resources and products along the whole value chain, connected devices can generate valuable data and information, which in turn may enable resource efficiency improvements or better end-of-life management. In transportation, autonomous vehicles might help increasing the rate of utilisation of vehicles in the future, through sharing platforms and subscription models. Consumers' use of IoT is facilitated through internet-connected appliances such as lighting, washing machines and printers, which enable them to increase their awareness and to take control of their energy consumption.

Many sectors benefit from IoT applications. For instance, energy companies are introducing smart power meters and smart household devices, which adjust the electricity consumption to the supply and demand of electricity in the grid (OECD, 2016[126]). Within built environment, cities have started to implement IoT monitoring for predictive maintenance and to optimise transport flows with adaptive signal control systems (Tomas, 2017[128]). In manufacturing, increased data availability through interconnected sensors may enable a more efficient use of resources and greater use of customised outcomes (OECD, 2016[126]).

Big Data Analytics

Big data commonly refers to large datasets usually characterised by their high volume, velocity and variety (OECD, 2015[124]).[18] Yet, big data is not just the collection of enormous volumes of data. While big data "lakes" can have value in themselves, most of their value depends on the capacity to extract information from the data, the analysis and consequential insights for decision-making. Big data analytics thus represents the datasets along with a set of techniques and tools which are used to process and interpret data generated by the ever-increasing digitisation of content, tracking of human activities, and connectivity of physical objects (OECD, 2017[1]). A variety of analytical tools is used, for instance for data mining, profiling, visualisation, and machine learning within AI. Additionally, the use of big data analytics enables data-driven innovation (DDI) with the potential to improve productivity of processes, organisational

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[18] While volume refers to the large amounts of data generated, variety refers to different formats of data (ranging from text, video, images, documents, to sensor data, activity logs, click streams, and coordinates), and velocity denotes the high speed at which the data is generated and changes over time.

methods and markets (OECD, 2015[124]). Big data itself relies on availability of cheap and large processing power and storage capacity, as well as on complex algorithms (OECD, 2017[1]).

Within the context of the circular economy, big data analytics can be applied to make more effective use of large information flows, for instance for monitoring processes of production and consumption, which may allow material flows to be optimised. One example is the application in precision agriculture, which measures, observes and responds to inter and intra-field variability in crops, aiming to optimise returns on inputs, while preserving resources (European Parliament, 2014[129]). Another example is Winnow Solutions which works with restaurants and other businesses aiming to cut down on food waste, using big data to identify how much food they are wasting and where they could save edible produce (Winnow Solutions, 2018[130]).

An important factor of production alongside labour and capital, big data has been revolutionising the way businesses across different sectors operate, compete and innovate (McKinsey Global Institute, 2011[131]). In manufacturing, sensor data is used to monitor the performance of manufacturing processes, to optimise operations, and to provide after-sale services such as preventative and predictive maintenance (Industrial Technology Research Institute, 2019[132]; Trotman, 2017[133]). Big data originating predominantly from geolocation allows transportation to be made more efficient, through better understanding and estimating users' needs in terms of routes and modes of transportation, real time estimation of traffic and congestion planning, and predictive analysis of traffic accidents (Intellipaat, 2019[134]). In retail and services, big data collected from social media, browsing behaviours, and in-store analytics is used to better understand consumer behaviour, which in turn allows for better understanding demand, forecasting consumer trends, creating smarter pricing decisions and cross-channel shopping experiences (Lebied, 2018[135]).

Artificial Intelligence

Artificial Intelligence (AI) can be characterised as a broad category of approaches that help make machines "smart".[19] Artificial Intelligence and cognitive-based technologies include the ability of machines and systems to acquire and apply knowledge, and carry out intelligent behaviour. The application of AI, which provides the ability to automatically learn and improve from experience, is called *machine learning*. The main value driver of AI is that it helps computers to interact, reason, and learn like human beings, enabling them to perform a broad variety of cognitive tasks that would normally require human intelligence (such as visual perception, speech recognition, decision-making or translation between languages). Intelligent systems in AI use a combination of other digital technologies, such as IoT, big data analytics, cloud computing and machine learning to operate and learn. In fact, the rapid diffusion of AI has been driven by advances in machine learning – an AI discipline which enables automatic identification of complex patterns in data sets, and the breakthroughs of which are driven by the availability of big data and cloud computing (OECD, 2017[1]). Combined with advances in mechanical and electrical engineering, AI technology has enlarged the capacity for robots to perform cognitive tasks in the physical world.[20]

AI applications hold many promises for the circular economy, creating value in terms of productivity gains, improving and automating decision-making, saving costs, and enabling better resource allocation (both in terms of factors of production and use of resources) (OECD, 2017[1]). Through AI, automation and robotics can venture into new fields, which so far required cognitive "human" thinking due to their complex decision-

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[19] There is no universally accepted definition of AI, but a widely used definition is provided by Nils J. Nilsson (2009[158]): "Artificial intelligence is an activity devoted to making machines intelligent, and intelligence is that quality that enables an entity to function appropriately and with foresight in its environment".

[20] Note that the OECD's Global Blockchain Policy Centre is exploring the benefits and risks of blockchain for economies and societies, identifying good policy and regulatory approaches, and investigating uses in specific policy areas (OECD, 2021[157]).

making. An example of the convergence between AI, sensors and robotics are waste sorting facilities equipped with robots, which are in charge of quality control of recovered materials and the separation of specific waste streams. The recognition of specific materials (through AI and machine vision) and their handling (with robotic arms) improve the quality and thereby also the amount of secondary material that can be further reused, reducing thus the demand for and dependence on virgin materials (and the externalities related to their sourcing and production) (Climate-KIC, 2019[136]).

Innovation enabled by AI is currently used to optimise and transform processes across industries, such as agriculture, energy, transport, healthcare, and finance. For instance, in improving energy consumption, Google has recently outsourced the control over cooling operations of several data centres to an AI based system. Using past consumption data, the system has acquired the knowledge to optimise energy consumption for cooling, leading to energy savings of around 40% in those cooling systems (Shead, 2018[137]). AI can also help optimising the logistics through estimation to logistics techniques. For instance, through the use of sensors monitoring vehicle performance and the behaviour of the driver, routing of deliveries has been seen to improve fuel efficiency by 15% for a trucking company (McKinsey Global Institute, 2018[138]).

Blockchain

Blockchain is a distributed append-only database, which is capable of storing any type of data, and is replicated across many locations operated jointly by all users. Once added to the blockchain, a record is encrypted and cannot be changed or deleted without the knowledge of all participants. This *immutability* feature of blockchain is what makes them strong and an alternative to traditional centralized databases. Instead, blockchain relies on a distributed peer-to-peer (P2P) infrastructure network for the storage and management of data, and the entire maintenance of the ledger. The computers (nodes) lend their processing power to the P2P network in order to validate transactions and ensure compliance with the underlying computer protocol (see Box A.1). Blockchain technology therefore eliminates the need for a central authority or intermediary in many processes, creates transparency, traceability, trust, and removes market friction and transaction costs (OECD, 2017[1]).

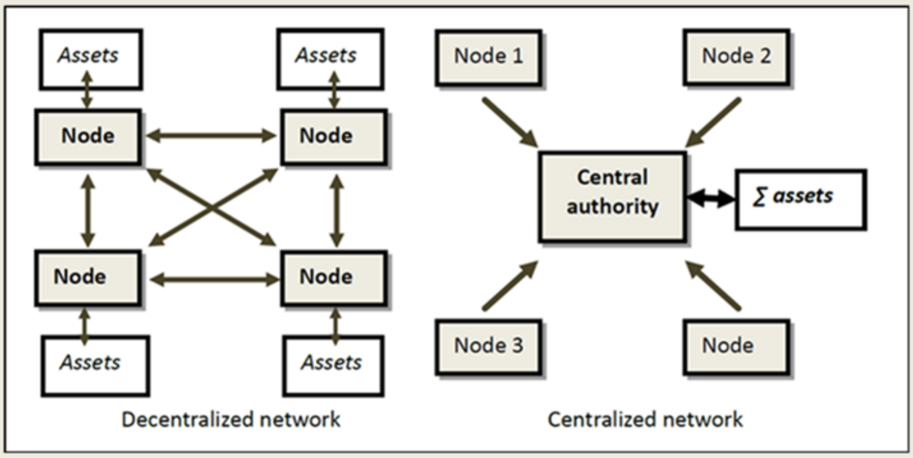
For the circular economy transition, blockchain technologies offer several opportunities that could enhance information flows, reduce transaction costs, and replace or improve monitoring and verification activities. Blockchain has been seen to enhance information flows along the value chain, and to improve the transparency and traceability for producers, consumers and recyclers (IFC, 2017[139]). Additionally, blockchain-powered *tokenisation* may drive the uptake of new business models, for instance through monetising plastic waste, or marketing the collected plastic to recycling firms with transparent information about its origin (Frankson, 2017[140]). Moreover, blockchain connected to *smart contracts* can facilitate peer-to-peer transactions, as well as enable micro transactions between IoT devices, replacing thus the need for monitoring and verification activities which are typically required with a centralised intermediary

The most widely cited example of a current blockchain application are *cryptocurrencies*. Digital tokens such as bitcoin, can replace the current means of payment and reduce thereby the transaction costs of payments, whilst maintaining a high level of security. Several applications outside of the financial sector also exist. In mining, blockchain technology can help assure and certify responsible sourcing of minerals. For instance, the provenance, authenticity and traceability within the diamond industry is assured by the combination of blockchain, IoT and AI. This end-to-end diamond industry traceability platform connects key stakeholders and thereby increases the availability of and accessibility to data, and enhances trust in the industry (in terms of responsible sourcing) (Tracr, 2018[141]).

Box A.1. The functioning of a decentralised blockchain network

A blockchain is essentially a decentralised peer-to-peer network of transaction confirmations and ownership transfers, without a central authority or intermediary. Computers on the network (the nodes) use cryptographic algorithms and smart contracts to confirm the transactions that are then written into blocks, and chains of such blocks form a ledger. When transactions occur, records of ownership (assets and their values) are permanently entered in ledgers and there are as many identical ledgers as the number of related nodes. This immutability feature of blockchains is what makes them strong and an alternative to traditional centralized databases. In theory, there is no need for an authorized intermediary to confirm the transactions and hence there is no need for a central database or repository of transactions and records. This mechanism results in a decentralised / distributed database of ledgers with a continually growing record of transactions. As illustrated in Figure A.1, this is in sharp contrast to a traditional centralized network, where all transactions are verified and ownership records kept by a central authority (Akgiray, 2019[142]).

Figure A.1. Schematic visualisation of decentralised (blockchain) network and a traditional (centralised) network



Source: Akgiray (2019[142]).

A blockchain network can be in one of two formats:

- Public (permission-less) blockchain: There is no one owner / operator and anyone is able to enter and exit freely. Everyone on a ledger has access to the same copy of the ledger and hence there are as many identical copies of a ledger as the number users. Bitcoin is a typical example of a public blockchain.
- Private (permissioned) blockchain: There are one or multiple owners / operators, who supply access interface to permissioned users. Only permissioned users hold a copy of a given ledger. Financial institutions seem to prefer this type of setup. Two examples are RippleNet and NASDAQ LINQ.Box heading - If you do not need a box heading, please delete this line.

Cloud computing

Cloud computing allows computing services to be accessed in a flexible and scalable on-demand way with low management effort (OECD, 2014[143]). Essentially, cloud computing can be thought of as a service-based business model for computer services (including software applications, storage capacity, networking or computing power), which can be accessed through an online interface (in form of a software, or extended to platforms). Cloud computing is a means rather than an end, and is often integrated with other digital technologies. For instance, it enables the networking and sharing of data that is collected by IoT sensors. AI algorithms and machine learning also commonly use cloud-computing power.

Moving physical services to digital services in the cloud can avoid resource use and waste. Netflix is one of the most prominent examples of cloud-enabled infrastructure. Similarly, streaming music through online platforms, such as Spotify, can substantially save costs, energy and materials otherwise needed to produce and distribute CDs. Amazon, one of the biggest players in providing cloud services, helps reducing the cost of system infrastructure by a third, and increasing the utilisation of servers as well as the efficiency in electricity use (compared to traditional in-house computing) (Nosratabadi, S., Atobishi, T., and Motaghi, 2018[144]).

The main value propositions of cloud computing platforms relate to accessing a shared pool of resources, quick and easy deployment of solutions, flexibility due to its scalability, reduction in ICT related costs, and pay-per-use or by-capacity-used. Cloud computing therefore allows lowering the entry barriers to high computing power or other costly computer services. According to a recent McKinsey study, the highest adoption of cloud computing (in terms of the relation between server images deployed and maturity of cloud capabilities) is in financial services, followed by healthcare and insurance (McKinsey, 2018[95]). However, players from other industries are also leveraging the public cloud.

Online platforms

An online platform is a digital service that facilitates interactions between two or more distinct but interdependent sets of users who interact through the service via internet, the collection and use of data about these interactions, and the network effects (West, Carblanc and Ferguson, 2018, forthcoming[145]; European Commission, 2019[14]). Online platforms enable innovative forms of production, consumption, collaboration and sharing through interactions among and between individuals, companies and organisations (OECD, 2017[1]). Online platforms therefore have the potential to create new markets, disrupt or enlarge existing markets, and optimise the matching of supply and demand for specific goods and services. The emergence of online platforms has already substantially changed consumers' behaviour in a variety of sectors. Most prominently, online trading platforms, such as Amazon, have transformed the way people shop, and e-commerce sales worldwide have rapidly increased in recent years.

Reducing friction, transaction and search costs for both buyers and sellers, increasing consumer choice, enabling new types of transactions, and improving efficiency and competitiveness of the industry being the main value propositions, online platforms can also drive business models for the circular economy (European Commission, 2019[14]). For instance, online trading platforms for used goods (such as E-bay, Gumtree or Craigslist) have greatly improved the market conditions for used goods. Beyond facilitating e-commerce trade of goods, online platforms have developed into service markets, helping to monetise abundant private assets (for instance accommodation and transport), and for any other type of service that can be delivered over the internet (such as part-time work by handymen, business consultancy or legal advice - e.g. Upwork and Freelancer) (OECD, 2017[1]). Furthermore, sharing platforms, such as Airbnb for apartments and Zipcar for cars, optimise the use of idle stock capacity (OECD, 2019[3]). Online platforms can also enable the provision of very niche goods and services with small markets where it would be otherwise unprofitable to sell, offering opportunities for specialised replacement parts among others (Anderson, 2004[146]).

Over the past two decades, online platforms have enabled the creation of exponentially growing online market places for products and services. Today, an estimated 1 million of businesses from across all sectors in the EU are selling their products and services through online platforms. These enable also small and medium sized enterprises (SME) to sell cross-border and in real-time. Additionally, online platforms also facilitate matching demand and supply of information, social media and creative content outlets, price comparison websites, platforms for the sharing economy, as well as online general search engines. Their importance is further underpinned by national and supranational legislation, as is for example the EU's Digital single market strategy (European Commission, 2019[14]).

Additive manufacturing (3D printing)

Additive manufacturing is a technique of manufacturing by successively adding layers of material, rather than removing it. Thus the label "additive". While additive manufacturing techniques have been used for some time now, they have gained widespread applications with the rise of 3D printers. The terms 3D printing and additive manufacturing are increasingly used interchangeably, referring to the "layer-by-layer creation of physical objects based on digital files that represent their design" (Petrick and Simpson, 2013[147]).[21,22] 3D printing is not a digital technology in itself, but rather an application of digital technologies to existing techniques of additive manufacturing. The OECD Digital Economy Outlook refers to 3D printing as an application that is enabled by AI, big data and simulations (OECD, 2017[1]). Within this paper, 3D printing is considered an individual digital technology, due to the prospects of enabling circular economy.

Additive manufacturing can reduce waste during production processes. While most common manufacturing methods involve materials being parts and products being carved out of a large piece of material, additive manufacturing uses exact amounts of material required to produce the desired product. More importantly, digital additive manufacturing techniques can enable decentralised manufacturing of complex (replacement) parts and "democratise" manufacturing (OECD, 2017[6]). This in turn has the potential to fundamentally transform manufacturing supply chains

The main value drivers of 3D printing are simplified manufacturing processes, rapid prototyping of even complex structural components, faster and novel design, product customisation (i.e. creating more functional and efficient products), make-to-order and provision of spare parts (i.e. creating potential for increased repair and remanufacturing), and cost reduction. Additionally, the increasing quality of printed objects and deployment of new materials in printing (such as glass, biological cells, and liquids, on top of the usual polymers, metals and ceramics) have been driving the expansion of 3D printing (OECD, 2018[10]). While 3D printing is largely seen as a technique to produce parts (for instance Boeing is using 3D printing to create more than 50 000 units of over 900 distinct parts for both its aircraft and spacecraft (OECD, 2018[96])), its applications range from more mainstream low-cost prototyping, design and manufacturing, vehicles, and housing, to more high-end bioprinting of human tissue and organs, as well as printing of bionic body parts.

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[21] Hereafter the term 3D printing will also be used to encompass the broader range of digital additive manufacturing techniques.

[22] A future technology of 4D printing is currently under development, which will enable a 3D printed object to transform itself into another structure, over the influence of temperature or light (Papageorgiou, 2017[149]).

Annex B. Glossary

Additive manufacturing	Also known as 3D printing, builds products by adding material in layers, often using computer-aided design software. It offers a customisable alternative to traditional mass-production technologies, allowing to print multi-structure multi-material objects.
Artificial intelligence (AI)	A broad category of approaches that help make machines “smart”. Artificial Intelligence and cognitive-based technologies include the ability of machines and systems to acquire and apply knowledge and carry out intelligent behaviour.
Automated objective grading technology	Improves the visual and mechanical inspection of physical and cosmetic conditions of refurbished connected devices, providing information about their actual state, detecting damages and defects, and allowing consumers to better understand the right value of refurbished devices and parts.
Big data analytics	Refers to large datasets usually characterised by their high volume, velocity and variety. Big data analytics represents the datasets along with a set of techniques and tools that are used to process and interpret data generated by the ever-increasing digitisation of content, tracking of human activities, and connectivity of physical objects.
Building information modelling (BIM)	Digital platform used in construction management to ensure that information is recorded at each stage of design, construction and operation of buildings. Contributes to design optimisation and provides insights into functional considerations of constructions and their environmental impact and cost predictability.
Blockchain	A distributed append-only database, which is capable of storing any type of data, and is replicated across many locations operated jointly by all users. Once added to the blockchain, a record is encrypted and cannot be changed or deleted without the knowledge of all participants.
Circular business models	Allow firms to create, capture, and deliver value through fundamental changes in production and consumption patterns, and thereby facilitate the transition to a more resource efficient and circular economy. The five key business models include: circular supply, resource recovery, product life extension, sharing, and product service systems.
Citizen participation platforms and mobile applications	Allow better informed development of citizen-driven policies and services and a more transparent and efficient civic engagement.
Cloud-based design and manufacturing (CBDM)	Also known as manufacturing as a service, enables distributed manufacturing, on-demand resource sharing and cooperative work across value chains. Service-oriented networked models allow configuring engineering designs of products and services and reconfiguring manufacturing systems, and ultimately facilitate open innovation with faster time to market, reduced costs, as well as improved information sharing, resource reuse and machine utilisation.
Cloud computing	Allows computing services to be accessed in a flexible and scalable on-demand way with low management effort. Cloud computing can be thought of as a service-based business model for computer services (including software applications, storage capacity, networking or computing power) that can be accessed through an online interface (in form of a software, or extended to platforms).
Combinatorial power	Digital technologies do not function in isolation, but are combinatorial, and function as part of the ecosystem that underpins the digital transformation.
Computer aided design (CAD)	Assists the creation, manipulation, analysis and optimisation of the design of customised products with complex geometries. Contributes to design optimisation and provides insights into functional considerations of constructions and their environmental impact and cost predictability.
Condition-based manufacturing	Enabled by remanufacturing data and information on wear and tear of each component, allows determining the extent of repair required (i.e. whether serious repair is required as opposed to a small brushing up or no repair at all).
Consumption externalities and risk aversion	Related to consumers’ misperceptions about low relative qualities of final goods produced from secondary materials. They might prevent some secondary materials to be used in applications for which they are perfectly appropriate.
Dematerialisation	Offers users product functionalities in form of services, by connecting assets (the provision of which might otherwise be hampered by prohibitive search costs related to limited knowledge on their availability and consumer preferences and behaviours) and selling them as services.
Digitalisation	Enabled by digitisation and interconnection, digitalisation represents the use of digital technologies for transforming value chains, changing the structure and operation of markets, enabling creation of platforms and ecosystems, affecting consumer behaviour and how relationships are developed, maintained and advanced, increasing the value retention, and mitigating some of the environmental externalities.

Digital passports	Also known as cradle to cradle passports or material passports, are database-backed digital reports that "travel" with physical products, provide an auditable record of their journey from design to end-of-life stages, and carry information on product compositions and embedded material types and grades.
Digital sourcing platforms	Also known as material exchange platforms, facilitate exchange of products and materials at their highest value reuse opportunity across different industries.
Digitisation	Conversion of an analogue signal conveying information (such as sound, image, or printed text) to binary bits and digital data, which can be used (i.e. processed, stored, filtered, tracked, duplicated and transmitted) infinitely by digital devices without degradation, at high speeds and at negligible marginal cost.
End-to-end traceability of certifications	Allows protecting producers' reputation and informs consumers about quality, origins and authenticity of products along the value chain. End-to-end tracking of material flows allows responding to uncertainty about quality and availability of supply of recycled materials.
Digital twin	A digital copy of complex physical products, services or processes. Allows monitoring the status and the position of components and specific product uses, enabling easier maintenance and repair through timely identification of problems preventing downtimes and facilitating product redesign and optimisation.
Imperfect information	Triggered by asymmetric or inexistent information exchange between different actors along the value chain about the condition and availability of components and products, composition of waste streams, as well as quality of secondary materials. This leads to inadequate traceability of products, components and embedded materials, as well as lack of trust in their reuse and recycling.
Industry 4.0	Also known as the fourth industrial revolution, refers to the use of emerging, and often interconnected digital technologies, which enable new and more efficient processes in industrial production, and generate digitally enhanced traditional and new goods and services, products and business models.
Intelligent assets	Physical objects that are enabled to sense, record and communicate information about themselves and their surroundings, through the application of digital technologies.
Interconnections	Allow data processing to occur globally.
Internet of materials	An open-source decentralised database of digital identity of physical materials, components and products. It allows customers scanning products and accessing raw material-related information from mill to the end product, creating trust and transparency without giving up confidential business information.
Internet of things (IoT)	An inter-networking of physical devices and objects, whose state can be altered via the internet, with or without the active involvement of individuals. It includes sensors that gather data and exchange these with one another and / or with humans.
Market failures	Also known as market inefficiencies, impede the well-functioning markets through inefficient allocation of resources. In this context, they negatively affect the scalability of circular activities.
Materials parsimony	Allows minimising the different types of materials used in manufacturing of products. It contributes to standardisation, simplifies sourcing and manufacturing and drives down the material demand and costs. It also makes product maintenance, reuse, remanufacturing and subsequent end-of-life collection, sorting and recycling easier.
Online platforms	A digital service that facilitates interactions between two or more distinct but interdependent sets of users who interact through the service via internet, the collection and use of data about these interactions, and the network effects. Online platforms enable innovative forms of production, consumption, collaboration and sharing through interactions among and between individuals, companies and organisations.
Peer-to-peer trading platforms	Platforms for commodities trading ensure efficiency and transparency along the supply chain, ensuring origin, quality, compliance and handling of raw materials.
Predictive maintenance	Allows replacing required components at required time, detecting machine conditions that would otherwise lead to failure and estimating the amount of time before such failure occurs.
Print-on-demand	Allows printing parts locally and on demand. It not only speeds up the procurement process and allows customisation, it also reduces the logistics required to transport and store large inventories of spare parts, decreases material uses and minimises waste while production.
Radio Frequency Identification (RFID)	Attached to materials, components, final products, waste and recycling containers, it enables better waste collection and recycling. A combination of sensors, identification technology and internet connectivity, RFID tags help implementing volume based waste charging systems and optimising municipal waste collection in cities.
Rebound effects	Translate into increased levels of production and consumption, which offset increases in production and consumption efficiencies. In circular economy, increased levels of production and consumption of digital goods (e.g. electronics) and services (e.g. energy / material intensive services, such as cloud computing), may offset the increases in production and consumption efficiencies gained through digitalised circular economy activities.
Recycling robots	Allow detecting parts of products and stripping them out safely and efficiently during the dismantling process.

Smart contracts	A transaction protocol that facilitates, verifies, and enforces the performance of a contract. Backed by blockchain-based communication protocols, QR codes and RFID tags attached to materials, components and final products, they permit trusted transactions and agreements to be carried out among disparate, anonymous parties without the need for a central authority, legal system, or external enforcement mechanism.
Smart questioning	An open-source decentralised database of digital identity of physical materials, components and products. Allows stakeholders to ask product-related questions and receive trusted answers based on smart contracts, creating trust and transparency without giving up confidential business information.
Smart waste management	More efficient waste collection and recycling based on asset tracking. It helps tracking the status of containers (in terms of their material content, fill levels, and need for repairs), oversee route management and fleet productivity, assure safety conditions, as well as more effective and cost-efficient sorting, reuse and recycling.
Technological externalities	Related to resource recovery and decentralised manufacturing of components or final products. They create complexities in optimising circular design and consumption, and hinder efficient dismantling and material recovery.
Transaction costs	Related to finding and bargaining with customers and suppliers, as well as those related to uncertainties around waste generation and composition. They may slow down the adoption of some of the service models, incurring higher capital costs, maintenance fees and virgin material consumption levels.
Urban modelling	An approach to abstracting reality to explain and predict urban spatial changes and the functions of cities in a simplified manner.