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1 Introduction

The digital transformation of society and economy has by now become a pivotal development of the 21st century, affecting every area of daily life, economy, policy, etc. Waste management - including waste prevention - and the more encompassing concept of a circular economy are no exemption to this. Digital technologies come with the promise of a more effective waste management regime, i.e. safer, more transparent, more economic and more resource-efficient processes, better sourcing of valuable material in the waste streams and an effective link to other sectors in a future circular economy.

This report analyses the status quo, chances and risks resulting from the digital transformation of the waste management sector. It shows that the waste management sector is in an early phase in this development. The chances as well as the impact of its digital transformation are still emerging and can still be shaped. The report wants to contribute to an improved understanding and management of this process. To this avail, it studies the relevant digital technologies in the sector, including present and future applications and the resulting potential benefits. It provides an understanding of the wider landscape that the digitalisation process is set into, and therein highlights the drivers and inhibitors that guide this development. Attention is also given to the external effects created by the digital transformation of the waste management sector in the economic, environmental and social realms. Moreover, hardly any sector is as closely linked to the emergence of a circular economy as waste management. Hence, the report also discusses how digital technologies are necessary and indeed indispensable to the creation of the circular economy as it is envisioned for example in the European Green Deal and the Circular Economy Action Plan.

The report is structured as follows: chapter 2 provides the required background and understanding on waste management, waste prevention and digitalisation as the central items of its investigation. In chapter 3 the forces that promote and hinder the digitalisation of the waste management sector are presented. The identification of the drivers and inhibitors shows where opportunities and necessities for digital technologies exist and which barriers may need to be overcome for their application. Chapter 4 provides insights into diverse digital technologies and how they are applied in the waste management sector. These technologies are illustrated by standardised profiles of current applications. How the waste management sector can profit from these technologies is shown in chapter 5, while the sixth chapter discusses existing and potential external effects. In chapter 7 the previous findings are put into relation with the emergence of the circular economy, specifically with regard to the novel EU's strategies for this field. Moreover, the chapter discusses why the establishment of a circular economy will inevitably require the use of digital technologies and how these can be applied in the overarching scheme and the different stages of the circular economy. Chapter 8 provides the conclusions for this study. It specifically addresses needs for further research and implications for policy makers. The key messages of this reported are summarized and presented in chapter 9.

2 Background information on digitalisation, waste management and waste prevention

This chapter provides background information on the topics underlying this report. Digitalisation, waste management and waste prevention are defined and described.

2.1 Digitalisation

European societies and economies have been experiencing a radical digital transformation, fostered by 'digitalisation' and the speeding up of many kinds of interaction through the increasing number of connected devices and data flows (Negreiro, Tambiama - European Parliamentary Research Service, 2019)

Digital transformation is characterised by the European Commission (EC) as "*a fusion of advanced technologies and the integration of physical and digital systems, the predominance of innovative business models and new processes, and the creation of smart products and services*" (European Commission, 2017). It is important to dissociate the notion of 'Digitisation' from 'Digitalisation'. According to the OECD (Going Digital (GD) Horizontal Project, 2017), 'Digitisation' refers specifically to the conversion of information or data from analogue to digital format while 'Digitalisation', refers to the adoption or increase in use of digital or computer technology (by an organisation, an industry, or a country) and therefore describes more generally the way digital technologies are affecting economy and society.

According to the OECD and today widely accepted, this digital transformation can *"spur innovation and productivity growth across many activities, transform public services, and improve wellbeing as information, knowledge and data become more widely available"* (Going Digital (GD) Horizontal Project, 2017). The World Economic Forum estimates that the combined global value of digital transformation to society and industry will exceed US$100 trillion by 2025, the European Parliamentary Research Service identified that an efficiently functioning digital single market could contribute €415 billion per year to EU economy for the period 2014-2019 and create hundreds of thousands of new jobs. Due to this enormous growth potential for EU business and society, fostering digital transformation is higher than ever on the EU's political agenda (Digital Europe Programme, 2019). It is indeed considered by the EC, that *„EU businesses are not taking full advantage of these advanced technologies or the innovative business models offered by the collaborative economy"* and that *„the state of the digitisation of industry varies across sectors, particularly between high-tech and more traditional areas, and also between EU countries and regions"* (European Commission, 2017). This variation across countries for the waste, water and sewage sector is illustrated in Figure 2.1. It depicts the digital maturity[1] of some EU countries with regard to a number of selected dimensions shown on the horizontal axis.

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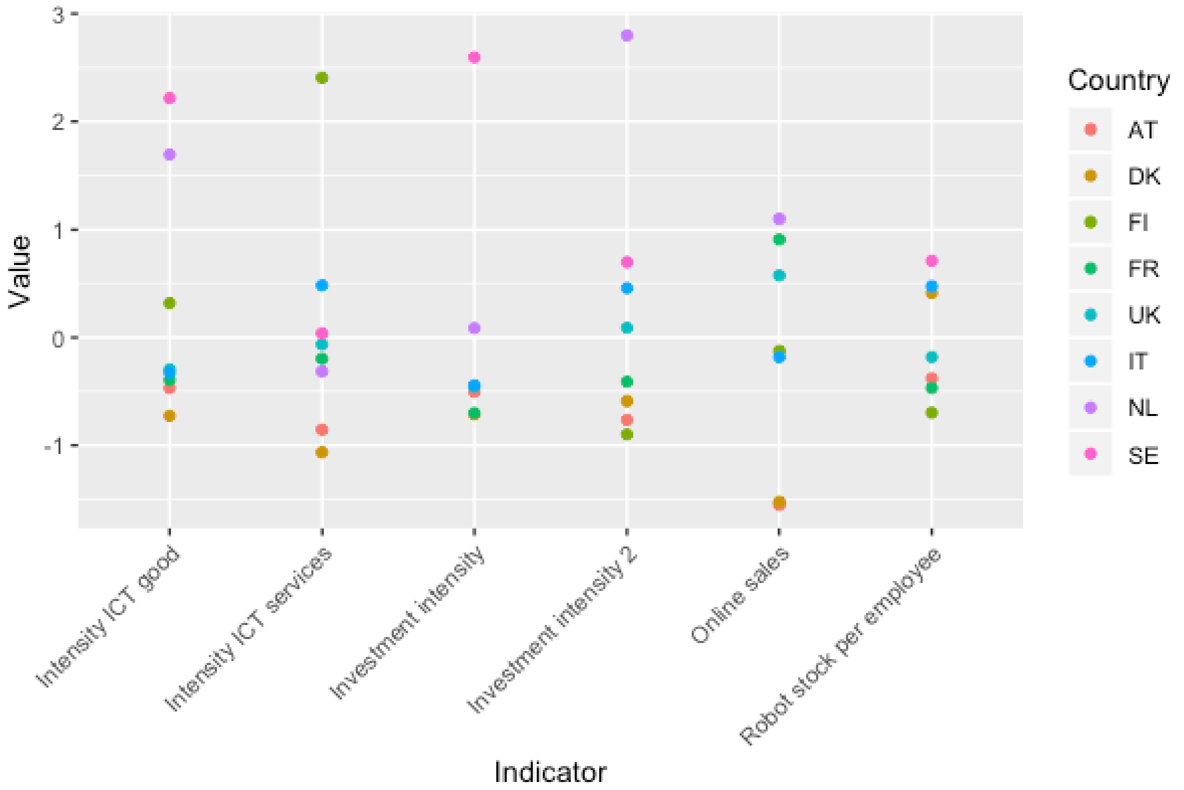
[1] According to OECD, 2019b: "The digital transformation is a multifaceted and fast-moving phenomenon that has significant impacts, including on the business processes and models of firms. As a result, the pace of technology uptake will depend, among other factors, on the type of sector in which a given firm operates. While no single indicator is able to reflect the pace of technology development and diffusion, combining indicators can provide insights into how different sectors are positioned in terms of technology adoption. Industries can then be classified into quartiles from most to least digital intensive which allows cross-country comparisons across a number of dimensions by digital intensity of sectors."

Figure 2.1: Spread of digital maturity for EU countries and different indicators for the waste, water and sewage sector. The y-axis shows data normalised for each indicator. Scattered points show heterogeneity while lumped points would stand for a similar status for all countries. Data adapted from OECD scoreboard.



Source: OECD – Organisation for Economic Cooperation and Development, 2017a

In order to provide an overview of the current implementation of digital technologies within the waste sector, it is first essential to define and dissociate the notions of waste management and waste prevention.

2.2 Waste Management and Waste Prevention

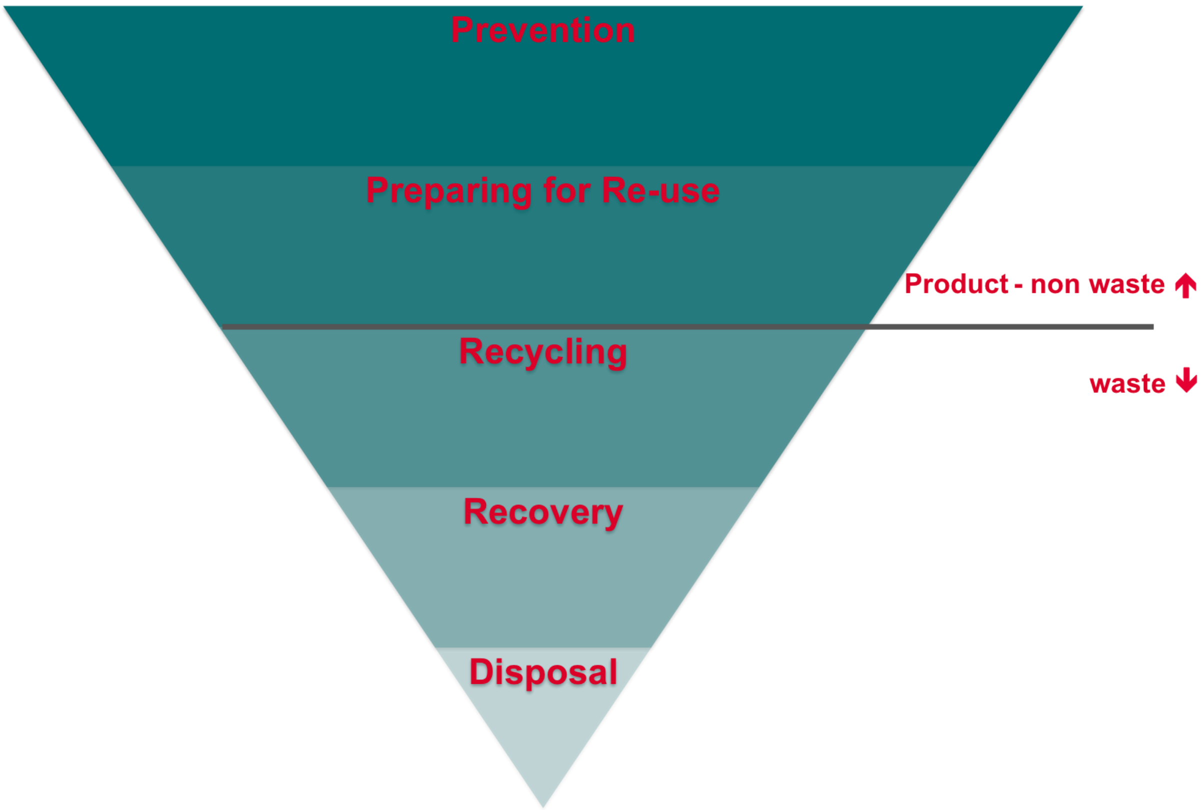
Waste management is defined as "the discipline associated with control of generation, storage, collection, transport or transfer, processing and disposal of waste materials in a way that best addresses the range of public health, conservation, economic, aesthetic, engineering, and other environmental considerations. Its scope includes planning, administrative, financial, engineering, and legal functions" (European Parliament, 2015; ISWA, 2011). Directive 2008/98/EC sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling and recovery. The directive defines when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products.

Waste prevention is defined as "measures taken before a substance, material or product has become waste, and that reduce:

a) the quantity of waste, including through the reuse of products or the extension of the life span of products;
b) the adverse impacts of the generated waste on the environment and human health; or
c) the content of harmful substances in materials and products" (Directive, E. C., 2008).

The amended Waste Framework Directive (EU) 2018/851 reiterated the importance of waste prevention by confirming its place as a top priority for waste legislation, according to the so-called waste hierarchy, as depicted in Figure 2.2.

Figure 2.2: Waste hierarchy with the most ecological options at the top. Adopted from EEA report



Source: European Environment Agency, 2019a

The waste hierarchy has been governing waste policy in Europe since the introduction of the Waste Framework Directive in 2006. The introduction of the waste hierarchy shifted waste management from processing large volumes of waste towards the creation of value. This led to a shift in focus from large volume, low value materials to low volume, high value materials such as copper and gold. They appear in electronic waste or used cars, which require thorough processing in order to extract the metals. Waste treatment activities became more complex and capital intensive. This brought a need for efficiency that resulted in the continuing search for new technologies. At the same time, this resulted in a tension between waste regulation and market drivers for material recovery and recycling. Waste was no longer processed close to the source, but rather at the place of higher market price, lower cost or less stringent environmental legislation.

At present the waste management sector experiences a strong development towards a circular economy. It is no longer motivated by the value of, for example, recycling in itself, the driver is increasingly becoming the constraints on materials. Several resources like chrome, cobalt, fluoride or rare earth elements are scarce. If their deposits are located in countries beyond the European sphere of influence or will be depleted in the future, it is of strategic importance to be able to recover these resources from the products in which they have been used. Our economy is in need of these and other critical materials, and these will be harder to purchase or more expensive to get in the future. This drives a new policy idea, which not only pursues the goal of how we can use more recycled materials, but also looks at the use phase of materials and products. It asks the question how we can increase the lifetime of products and keep materials at a high value throughout their life cycle.

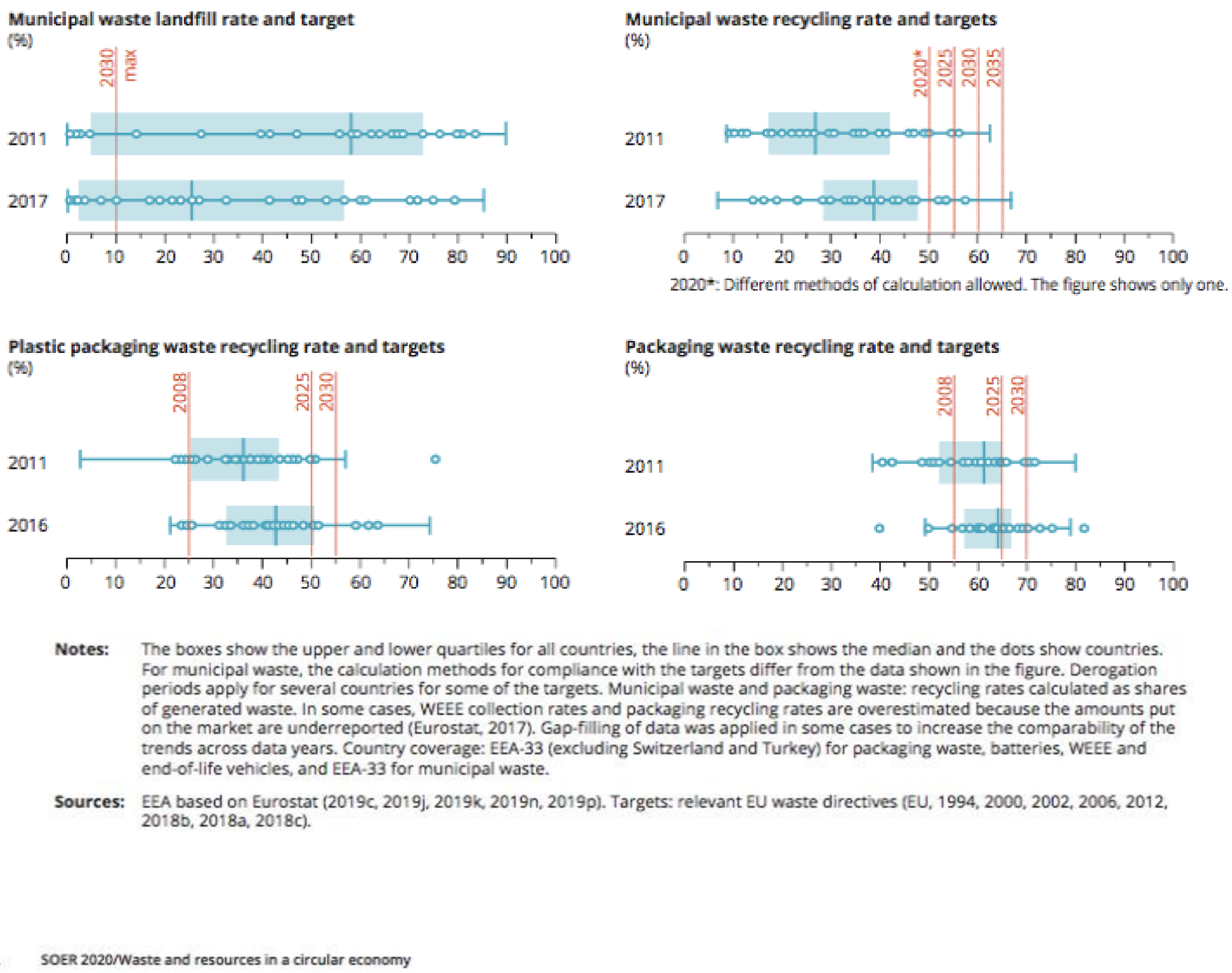
In a circular economy, the distinction between raw materials, products and waste becomes increasingly unclear. Material management is part of the product value chain and producers remain responsible for the product and material that they place on the market. In leasing models, producers even keep the ownership of the product and provide only a service to the customer. This could have fundamental effects on the waste sector, and existing players need to redefine their role in this complex system of material management. This again drives the integration of innovative technologies that can be supplied through digitalisation. This development will be intensively analysed in the following chapters.

3 Understanding the landscape: Drivers and inhibitors of the digital evolution of waste management

Digitalisation is not an end in itself, the application of digital technologies should rest on their ability to create new chances or solve existing problems in the waste management sector. To understand where such opportunities and challenges lie and what the limiting factors are, this chapter identifies the major drivers - which may take the form of chances and challenges - and inhibitors of the digital transformation of waste management.

Taking a European perspective, it is important to understand that countries are on different levels regarding their advancement in waste management in general (compare), making one driver applicable for some countries while it does not apply to others (European Environment Agency, 2019b). The graphs show that many countries still have a long way to go to make their waste management conform to EU targets - or to a higher standard for non-EU countries. This indicates that many more and specifically regulatory measures will be needed to create a more sustainable and circular waste management. This working paper illustrates how digitalisation can be a part of that.

Figure 3.1: Heterogeneous situation in waste management illustrated by different progress on waste management goals



Source: adapted from European Environment Agency, 2019b, p. 224.

Before looking at specific digital technologies currently applied in waste management in chapter 4, it is important to understand the underlying forces that have so far promoted or inhibited the digitalisation of waste management. Such drivers and inhibitors were identified in earlier research by the researchers of this study, especially for Germany (Berg et al., forthcoming). However, based on our research and expert interviews conducted within the framework of this study we also know that many of them account for Europe in general, although potentially to different degrees in different countries depending on the respective state's advancement in digitalisation and waste management. The work also indicated that privately owned companies may be more advanced than state owned ones.

3.1 Drivers

Driving forces can take the form of opportunities, where the application of digital technologies directly improves a given context or process, or challenges, where current negative developments can be countered or alleviated. Most of these drivers are not uniformly distributed, instead they act differently in different regions according to their unique characteristics such as population, economic strength, etc. Drivers identified in this regard are urbanisation, demographic change, skill shortages, novel legislation, cost pressures, expectations from citizens and customers, and new business models, which are described in more detail below (for both drivers and inhibitors cf. Berg et al., forthcoming).

- **Cost Pressure** – Competition among commercial waste companies and money allocation for the public waste sector, respectively, leads to cost pressure. This can be counteracted by increased efficiency through digital technologies. For the commercial market, the shift from labour to capital is an important factor as well, that can act as a driving force for digitalisation.
- **Business Models** - In the process of digitalisation, new digital business models emerge, often invented by new competing players. These will force established players to follow, and lead to more applied digital tools. While the waste sector is less affected, since waste as such is not easily virtualised, still some aspects of the business see an impact. Especially trading on virtual platforms is an emerging point in place.
- **Customer Expectations** - In the course of digitalisation, many customers are used to having near real time information on status of orders or to be able to monitor their utilities. These expectations presumably apply to the waste sector as well and can only be met by digital solutions such as tracing and tracking or telematics[2] interlinked with each other. Real time insights into the provision of certain services, like waste collection, already exist in some municipalities.
- **Pull towards Circular Economy** - Current visions for a shift from the linear waste model to a circular economy require new innovations, including many digital ones. These range from digitally advanced maintenance to sorting enabled by artificial intelligence. This shift is backed by international and EU politics.
- **Climate Crisis** - The pledge to reduce greenhouse gas emissions implies landfilling to be stopped (and the related methane emissions), and instead preferably prevent and recycle waste or incinerate where inevitable.
- **Extended Producer Responsibility (EPR)** - EPR systems have proven their value in the current materials management policy context. Those EPR schemes will be applied to many more products

[2] The term telematics is formed by the words telecommunication and informatics. Telematics focuses on controlling remote objects by transmitting data via telecommunication technology and enables monitoring, analysis and optimisation, which leads to many possible applications e.g. in vehicle tracking and fleet management.

to meet the political goals. Here, digital technologies can help tracking, monitoring and transferring materials and products throughout their life cycle.

- **Waste Amounts** - Waste amounts are still expected to grow slightly in the coming years (European Environment Agency, 2019b, p. 220). Handling and reducing these quantities in a circular economy will require extensive understanding (analysis) and management approaches, both politically and economically. The required actions can be much more effectively dealt with using digital technologies such as data analytics and advanced logistics.
- **Urbanisation** - Population has shifted considerably from rural areas to metropolitan areas. This trend is expected to last in many regions in the foreseeable future (BBVA Research, 2016). Hence, differences in population density increase, resulting in highly populated cities and their surroundings and a less populated countryside. Rising population density in areas also increases traffic intensity, bringing along challenges in waste collection services. Moreover, plant capacities will have to be increased. Technologies like digitally advanced logistics, traffic-oriented collection schemes, automation and robotics can be used to address these problems. Conversely, declining population densities result in lower utilisation rates of waste collection and existing waste treatment capacities. Such challenges can be met by digital technologies for example by using advanced logistics approaches like waste collection on demand.

Many of the above-mentioned drivers can be summarised as the need for improvement of certain aspects such as costs, efficiency or ecological footprint.

3.2 Inhibitors

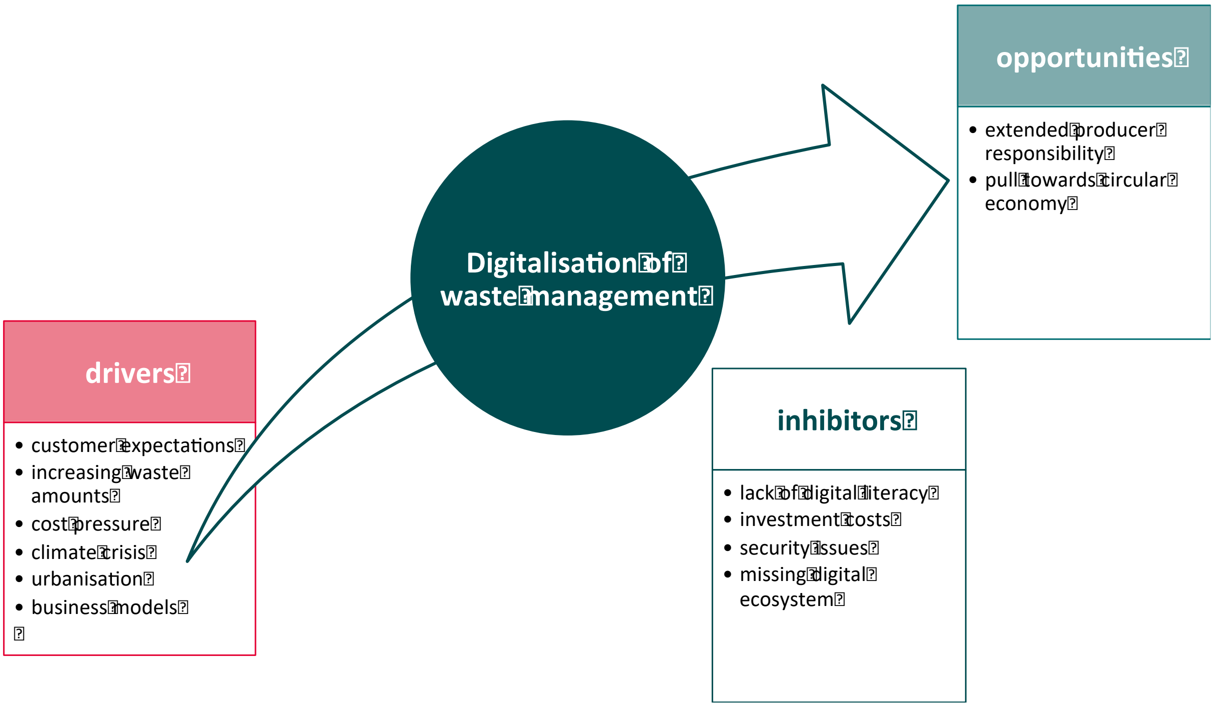
While there are many factors favouring and driving digitalisation, there are others that slow down its speed or prevent the application of digital tools due to certain problems. It is important to also understand these forces as they influence the effectiveness of digital technologies and the chances of their application.

- **Digital Literacy** - Skilled workers with digital abilities are necessary to implement and maintain the digital tools. However, there is high demand for such employees in the whole labour market currently, and therefore competition is intense for these skills on the labour market. It is especially hard for the public sector with rather small and fixed wages to compete for these people. Subcontracting or outsourcing these tasks might be a possible way to deal with this problem, yet affecting the cost structure. In general, it can be said that especially in a quick changing digital world, training of personnel will play an important role. Moreover, a change towards the use of digital technologies can imply a change in workforce structure. Unskilled or less educated staff in collection and sorting could be replaced by fewer but higher skilled technology experts.
- **Costs** - Digital solutions often need high upfront investment and will only pay off over the years. Especially with functioning technologies still in place, this will lead to a slower change in technology, especially on the side of public actors.
- **Security** - Waste management as a critical infrastructure must rely on operational and secure soft- and hardware for its main tasks. Security of IT Systems is therefore critical, as these infrastructure systems are high priority targets for foreign offensive IT-warfare operations or other groups and people. Therefore, software must be well designed and thoroughly checked. These circumstances lead to longer development times and higher development cost.
- **Digital Ecosystem** - For many of the new digital solutions, to work effectively, an existing digital ecosystem is required, as most of these solutions cannot be designed stand-alone but rely on a balanced system of legal frameworks, broadband access and mobile network coverage, standards for data exchange, interfaces and public digital literacy. In earlier research we found that

specifically a lack of interfaces between different software systems and applications within organisations and between steps in the production and waste management chain is a major inhibitor in this regard (Berg et al., forthcoming).

Figure 3.2 summarizes the drivers and inhibitors described in the preceding chapter. The next chapter gives an overview about key digital technologies and their current application in waste management.

Figure 3.2: Drivers and inhibitors for the digitalisation of waste management, with drivers being represented by opportunities and challenges

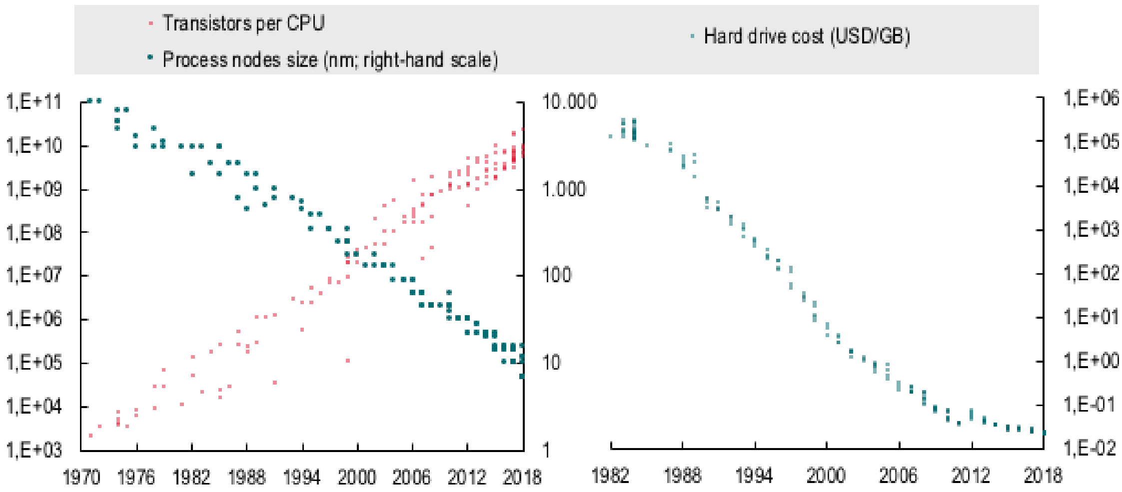


4 Digital technologies and their current use in waste management

4.1 Overview of digital technologies

With the first semiconducting transistors, a development began that has seen a steady rising trend up until now and is not expected to stop soon – digitalisation. In its early days the technology was used for mathematics, to compute numbers. The connection to sensors made it possible to collect larger amounts of data and laid the foundation for digital process automation and control engineering, which has transformed most of the manufacturing industry. At the same time, networks have been evolving, starting from local networks connecting computers by cables to eventually result in the internet with billions of wireless devices connected today. Some indicators for this development are plotted in Figure 4.1, where the development of computation power and data storage costs is shown for the last decades.

Figure 4.1: Development of costs for computation power and storage



Source: adapted from OECD Employment outlook,OECD – Organisation for Economic Cooperation and Development, 2019a

Thanks to the trend of miniaturisation and the ongoing cost reduction, digital technology is applied everywhere: worn on the wrist as a smart watch, tracking animal movements all over the world, or travelling to the borders of our solar system as satellites.

Current important technological trends are robotics, the internet of things, cloud computing, artificial intelligence and data analytics. Because of their significance, also in the field of waste management, they are presented in more detail in the sections below.

Another important technological development of our time is the field of *e-commerce* and the digitalisation of trade. The shift from retail to online businesses has had profound impacts on various industries, changed business models, and has made data an important asset. This development has gone so far that the highest capitalisation today is in digital companies (Finanzen100, 2020). At the same time, the area of finance has seen a similar change. Stock trade today is governed by algorithms and computers competing against each other in high-speed trading. The development of Bitcoin in the last years has shown that digital, independent currencies can be implemented. E-commerce already has a profound impact on waste streams and waste management, for example, due to high numbers of returned deliveries which are being destroyed instead of resold. In Germany alone, nearly 20 million items are destroyed annually which corresponds to nearly 4 % of the returned goods (University Bamberg, 2019).

Another important trend is the automated analysis and evaluation of data in respect to *surveillance technology* and targeted advertisement. The People's Republic of China has installed around 200 million surveillance cameras in 2018 and is working hard to use these data for law enforcement (Paul Mozur - New York Times, 2018). The microphones, cameras and location sensors built into smartphones and smart-home appliances all over the world are not under steady surveillance, but can be easily accessed by intelligence services (Deutscher Bundestag, 2017). Surveillance also plays a role in waste management when sensors are used to monitor containers for level of filling and functional status. Also, behaviour towards waste can be measured and analysed, for example, the sorting behaviour of households or littering in public spaces.

The importance of digital technologies in personal and business life has caused steadily rising demands for *digital security*, another very important field of digital technologies. Since cybercrimes can be easily committed without physically being at the site, the barrier is low to attack promising targets. Thus, the development of *cryptography* methods has seen major advancements. The source of vulnerability is commonly a poor implementation into software or the false use of this software.

The following six subsections provide a more detailed view on six distinct technologies: robotics, internet of things (IoT), cloud computing, artificial intelligence and neural networks, as well as data analytics and distributed ledger technology. These technologies are expected to have a major impact on the waste industry.

4.1.1 Robotics

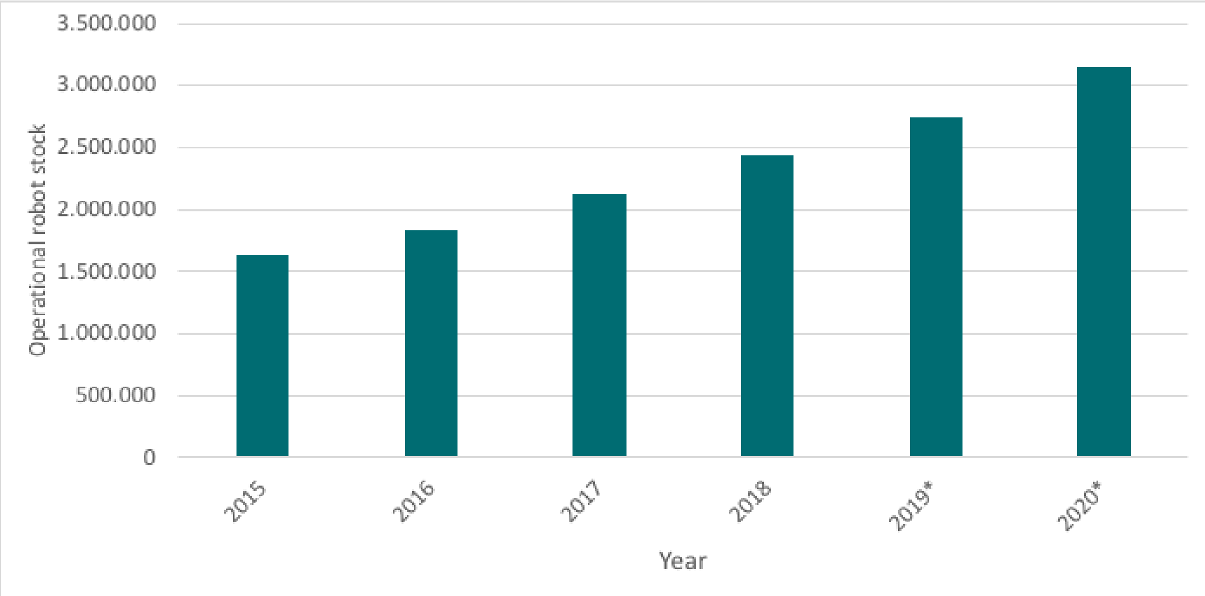
There is no generally valid definition for robots. Instead, those definitions that exist differ greatly with respect to the extent of autonomy, the area of application and capabilities. Two definitions are presented below:

- Robot Institute of America defines robotics as
  “reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialised devices through variable programmed motions for the performance of a variety of tasks” (Robot Institute of America, 1979)

- VDI -Guideline 2860 uses the following definition:
  “Industrial robots are universally applicable automatic motion machines with several axes, whose movements are freely programmable (i.e. without mechanical intervention) with regard to the sequence of movements and paths or angles, and are sensor-guided if necessary. They can be equipped with grippers, tools or other manufacturing equipment and can perform handling and/or manufacturing tasks” (Verein Deutscher Ingenieure e.V., 1990)

Most of these definitions however, are for specific types of robots and refer to machines that have different options of action, and that can execute these actions more or less autonomously. The great progress in the fields of mechatronics, in sensor technology and its production, as well as in computer science has, in recent years, greatly expanded the limits of robot autonomy. Even if individual robots, such as the mars rover or deep-sea diving robots, are meant for tasks that are not possible for humans to execute, most robots are built to replace human labour. This mostly concerns tasks that consist of a few similar steps and where necessary decisions are made according to clear, digital rules. In parallel to these advancements, the price of the necessary hardware has decreased to the extent that nowadays, specific robots are affordable for normal private individuals - a vacuum cleaner robot can be bought for about €100. As a natural consequence of this strong price reduction, the number of robots in various fields has increased dramatically, as is shown in . This trend has also affected waste management, even though the prevalence of robots is still low compared to other sectors.

Figure 4.2: Number of operational robot stock, nearly doubling from 2015 to 2020



Source: IFR - International Federation of Robotics, 2019

In the context of waste management, robotics is a two-faced technology. On the one hand, there have been major advancements in the pneumatic sorting process as a result of automation technology, which can be viewed as robotics, and we can expect further improvement in this area. These advancements allow producing defined waste streams of high purity which is mandatory for an efficient recycling process. Moreover, in the future there will likely be robotic technology facilitating the collection process as well as the logistics involved in waste handling. On the other hand, robots are involved in every part of the production process of modern goods, starting from resource extraction up until packaging and shipping of the final goods. This resulted in a major increase in productivity (IFR - International Federation of Robotics, 2017) and also spurred miniaturisation. However, all these goods produced end up as waste, once they are used and discarded. So, seeing the complete picture, automation and robotics are at the source of a problem they can help to resolve.

There are several examples of robotics in the waste management sector, representative ones are listed below:

- Apple (USA): The robot Daisy dismantles up to 1.2 million used iPhones per year enabling the recycling of the used materials including tin, aluminium and cobalt which is essential for building batteries (Apple, 2020).
- BHS (USA): MAX AI is a robot that is able to identify and sort recyclables through a vision system which is continuously improved by AI (BHS, 2020).

- Remeo and Zen Robotics (Finland): Robotic waste sorting station based on image recognition and IR scanning. One robotic arm can pick more than 2,000 items per hour increasing its precision (often over 90%) in a learning process (Zen Robotics, 2020).
- Refind Industries (Sweden): Machine that sorts common batteries based on their material. Can sort up to 500 kgs per hour with a 97% precision using AI (Refind Industries, 2020).
- Autowise.ai (China), Enway (Germany): autonomous, self-driving street sweepers (Autowise.ai, 2020, ENWAY, 2020)
- Volvo Group and Renova (Sweden): autonomous, self-driving refuse truck (Volvo Group, 2020)

4.1.2 Internet of things

Internet of things (IoT) refers to the trend that more and more devices are connected to the internet or other networks even though the primary purpose of these devices is not the connection. Examples in the smart home context are the digitalisation and networking of household appliances such as TV's, smart light bulbs, washing machines and refrigerators that can be accessed remotely or even communicate with each other. Other examples in the industry 4.0 context include the networking of production machinery together with monitoring the whole production environment, and in the traffic context the networking of road users and sensors that monitor the current traffic status.

A prerequisite for the IoT was the increase of wireless network and communication technology (mobile radio, Wi-Fi, Bluetooth, NFC). Miniaturisation and mass production of the required hardware are other important ingredients that led to this technology. Only because of this development, has it become possible and affordable to integrate connectivity and functionality into various devices. The fascination of this development lies in the expectation that data and functionalities which it makes available, open up completely new insights and possibilities. Predictive maintenance to reduce downtime, smart metering for supply-related power consumption or traffic jam reports based on user movement profiles are prominent examples. However, IoT also poses risks, such as the risk of totally monitored citizens, not only by the state but also, and above all, by companies or criminals who gain unauthorised access to the data collected in this way. The security of devices is another problem, for example, infected IoT devices are used for distributed denial of service attacks (Symantec Security Response, 2016) or there is the possibility to follow the live stream of thousands of surveillance cameras with inadequate access restrictions (insecarm.org, 2020).

For the waste and recycling industry, the opportunities of IoT exist above all in sensor-supported containers, in the simple, electronic processing of documentation, and in the networking of vehicles to improve logistics. Sensor supported containers collect data such as container location or filling level. This data is transferred to a central unit and used to optimise workflows such as pick-up routes. This technology is being employed at an early stage in some innovative cities. Electronic documentation can, for example, be facilitated by RFID[3]-tagged waste bins. They make it easy to document failure to collect or failure in sorting, or to detect waste bins that are not paid for. The technology is proven and has been applied for years – countries such as Germany have several million RFID equipped waste bins in use. In the long-term,

[3] Radio frequency identification (RFID) is used to identify and track tags attached to objects with the help of electromagnetic fields.

related technologies such as cyber physical systems and digital twins are expected to facilitate information flow to support recycling. Already existing examples and some under development are listed below.

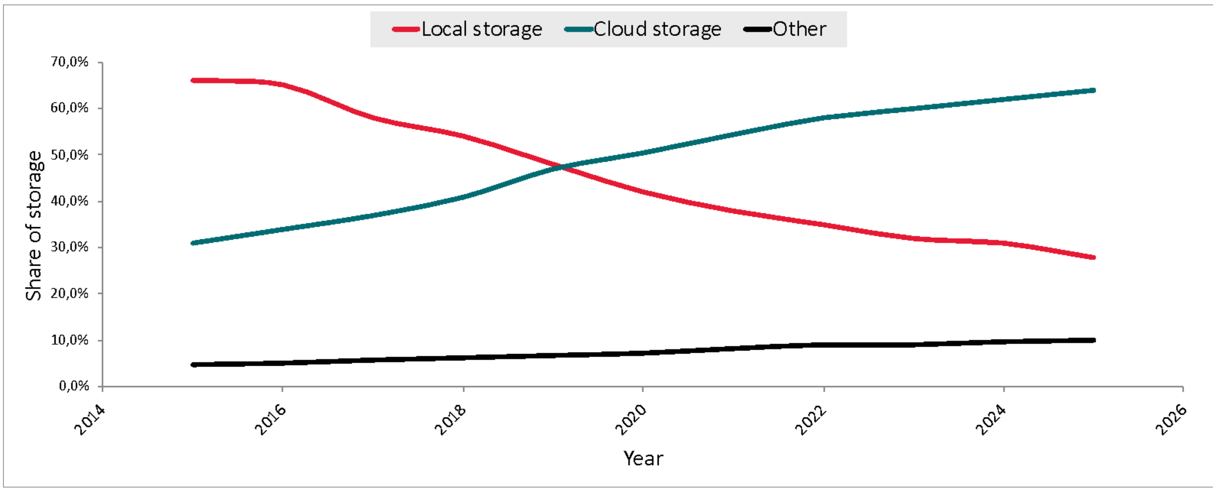
- Smart bins (remotly monitored and managed waste bins, enabled by level measurement): Bigbelly Inc. (USA) (Bigbelly Inc, 2020), Ecobins (Croatia) (Ecobins, 2020), Eco mobile d.o.o (Poland) (Eco Mobile, 2020), ECOnX Waste Solutions B.V. (Netherlands) (ECOnX Waste Solutions B. V., 2020), Nordsense (Denmark) (Nordsense, 2020), Oneplus Systems Inc. (USA) (Oneplus Systems Inc., 2020), SSI Schäfer (SSI Schäfer, 2020) , SmartBin Live(SmartBin, 2020)
- C-trace GmbH: vehicle systems for garbage trucks including ident-system (RFID-based identification systems for identifying bins and counting emptying) and weighing system for weight-based billing, incorporated into software modules (c-trace GmbH, 2020)
- Smart Recycling AB (Sweden): optimizing emptying logistics based on level sensors and GPS-coordinates of containers (Smart Recycling, 2020)
- StalkIT AS (Norway): tracing and tracking of items like containers by measuring and transmitting location, movement and temperature (StalkIT AS, 2020)
- teXXmo Mobile Solution GmbH: “IoT-Button”, a physical button that can be programmed to trigger predefined processes such as triggering collection of containers (teXXmo Mobile Solution GmbH, 2020)

4.1.3 Cloud-Computing

Cloud computing is a model that allows convenient network access on-demand, anytime and anywhere, to a shared pool of configurable computing resources. They can be made available quickly and with minimal management effort or service provider interaction (NIST - National Institute of Standards and Technology, 2011). These resources can be storage systems, applications and services, servers or networks.

As a result, IT services can be offered, used and billed dynamically adapted to demand. The range of services offered in the context of cloud computing covers the entire spectrum of information technology and includes infrastructure such as computing power and storage, but also platforms and software. Around 2020, the data stored in cloud-storage is expected to surpass locally stored data according to the Statista digital economy compass 2019, compare Figure 4.3.

Figure 4.3: Shares of local storage, cloud storage and other storage in the last years



Source: Matthias Janson - Statista Infografiken, 2019

This model creates the possibility of shared use of capital-intensive investment goods such as computing power or software. There are basically three categories of service models: infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS) (BSI - Bundesamt für Sicherheit in der Informationstechnik, n.d.). Cloud computing is used in the waste management industry in various applications. Examples are storage and processing of sensor data or software solutions for the management, collection, administration and documentation tasks. This cloud-based software can be billed on a pay-per-use or time limited license or can be open-source so that only the service fees for software administration and used infrastructure are billed. A list of software applications in the waste sector, relying on cloud computing, is given below

- ISB Global Ltd. (UK): cloud computing for Infrastructure, architecture, development and deployment of "SAP Waste & Recycling One" (trademark, ISB Global Ltd., 2020).
- MOBA (Germany): cloud computing for container management, customer management, tracking, navigation and route planning (MOBA - Mobile Automation, 2020).
- AMCS Group: connection, standardizing and optimizing internal procedures (AMCS Group, 2020).
- Waste Logics Software Ltd. (UK): Management software for multiple devices including functions such as real-time order management, route planning and optimisation, customer self-service, order-tracking and evaluation (Waste Logics Software Ltd., 2020).
- Samsara Networks Inc. (UK), Rubicon Global Holdings LLC. (USA), TouchStar Technologies Ltd. (UK): Vehicle life tracking, route planning, analysis and optimisation using cloud computing (Samsara Networks Inc., 2020, Rubicon Global Holdings LLC., 2020, TouchStar Technologies Ltd., 2020).

4.1.4 Artificial intelligence and neural networks

In general, intelligent systems are characterised by their ability to solve problems independently and efficiently (Mainzer, 2016). Artificial intelligence is trying to achieve that by using digital solutions. Several different approaches exist with the most famous one being machine learning using neural networks. It is based on the use of data or examples to solve problems without explicit programming. A typical example is classification/pattern recognition which is used in waste management context as well. Commonly, neural networks are used for this task, they consist of interconnected layers that compute the input information (Burgard, 2018). Large amounts of data are used to train these neural networks. Given the massive number of these layers, we speak of a deep network and deep learning in this context. The precision of the networks depends on how the layers are connected on the one hand, but on the other hand, largely on the amount and quality of the data used to train these networks.

Applications of this AI to the waste management sector are sorting applications that use image recognition, autonomous vehicles and sweeping robots. AI can also enable collection to take place at optimal times (route optimisation and predictive pick-up). A prerequisite for this is the existence or collection of data sets, for example, by equipping collection vehicles with sensors. AI can also be used in customer services, for example if speech recognition is used to route a call to the right employee or in training chatbots. This application can be very important in terms of service improvement and relieve of communication as well as service departments in municipal service centres. Moreover, citizen information services including correct forms of domestic sorting, waste management by households and so on can be more efficiently offered. In Hamburg, AI is used to classify illegally dumped waste through image recognition, in order to enable efficient removal. Specific examples include

- Autowise.ai (China), Enway (Germany): autonomous, self-driving sweeping vehicles that perform cleaning tasks in commercial or public areas (Autowise.ai, 2020, ENWAY, 2020).
- Volvo Group and Renova (Sweden): autonomous, self-driving refuse truck for curb side collection (Volvo Group, 2020). An increase in reverse driving enables time savings.
- Remeo and Zen Robotics (Finland): Robotic waste sorting station based on image recognition and IR scanning (Zen Robotics, 2020). Gripping robots scan waste objects and sort it into different containers. Through the application of AI, adaptation to new sorting fractions can be easily implemented.
- Stadtreinigung Hamburg (Germany): AI image classification for illegal littering. Citizens can take images of illegal littering with their smartphone. A software classifies the images and redirects it to the appropriate agent.

4.1.5 Data analytics

The process of digitisation has made the collection of large amounts of data much easier as activities are logged digitally (IoT) and thus create additional data. However, masses of data alone do not create much value, only the possibility to analyse data makes it so valuable. Data Analytics is the task of processing and analysing data in order to identify patterns, extract information, discover trends or calibrate models. In order to make the insights and knowledge gained through data analytics understandable, and to communicate them, visualisation is an important aspect of data analysis.

Data analytics plays an important role in the recycling industry, even if its use is not always apparent at first glance, since data processing is often automated and runs in the background. Examples are electronically supported disposition of waste collection vehicles, evaluation of sensor data for automated sorting plants, or control of waste incineration plants. All these technologies are used commonly today. An overview of waste quantities and material flows on regional or national level is also based on the collection and analysis of data. This knowledge is important in order to evaluate different options for the transition to a circular economy.

Examples for commercial technologies that are relying on data science are listed below.

- ReSource International: Drone based data collection on landfills (Resource International, 2020). Through the use of drones for aerial surveillance data for the monitoring of landfills is collected.
- CNIM Group (France): software for data collection, modelling and optimisation of energy from waste processes (CNIM Group, 2020). The company optimises its business of designing, building and operating waste treatment plants, by using data and software.
- BIR (Norway): platform for collection and evaluation of waste related data (BIR, 2020). A software solution that handles data from different business parts and allows to interchange that data and store it according to legislation.
- AMCS Group: connection, standardising and optimising internal procedures (AMCS Group, 2020). On the basis of operational, financial and performance data, the software helps to make decisions on optimisation, expansion and management of waste businesses.
- SmartBin (Ireland): Sensors for location and level of waste bins (SmartBin, 2020). Sensors can be retrofitted to existing containers and allow live monitoring of the fill levels of all containers. Routes can be optimised to collect only those containers that are necessary.

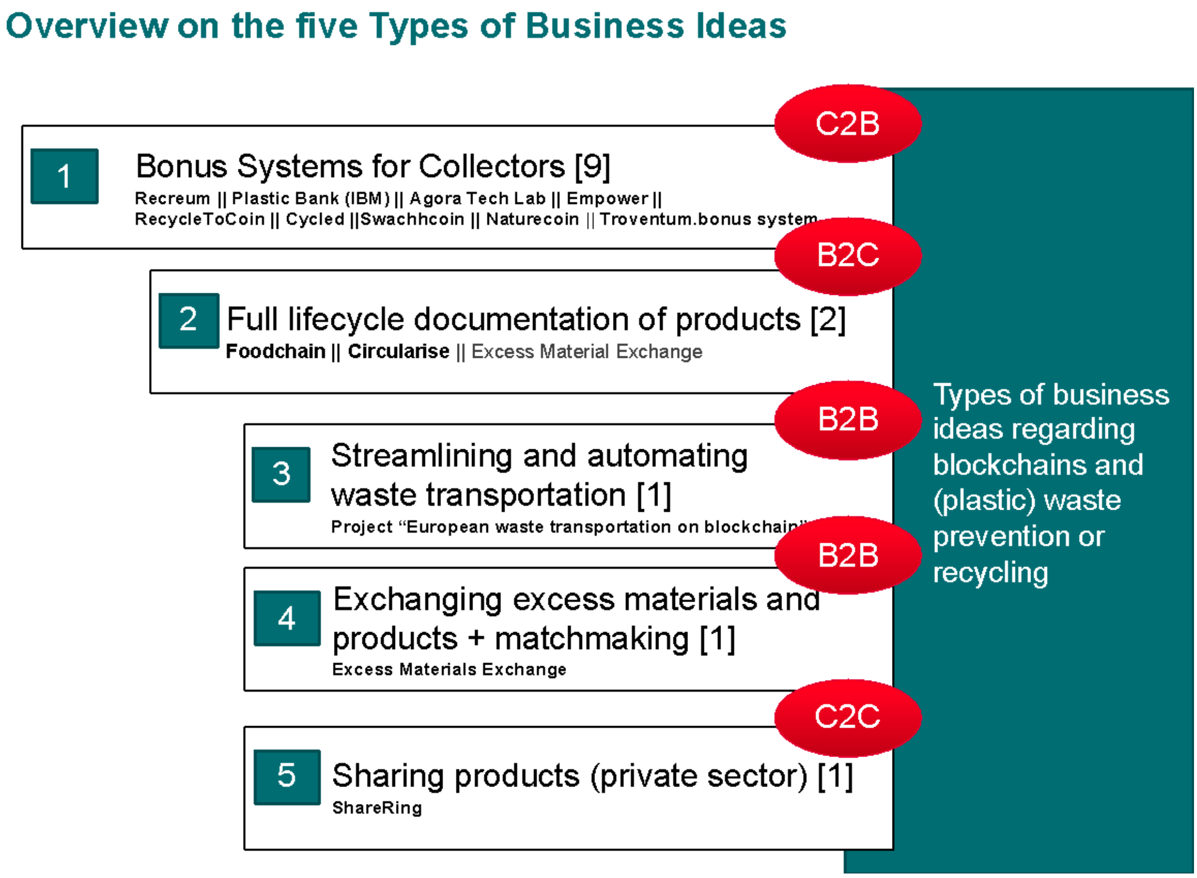
4.1.6 Distributed ledger

With the publication of a whitepaper on a digital currency by Nakamoto in 2008 the idea of blockchain and Bitcoin was born and the foundation for the distributed ledger technology was laid (Nakamoto, 2008). Distributed ledger technology (DLT) is in its broadest regards the idea of a decentralised database. While there are many approaches to store data on distributed servers, DLT differs from those. In DLT, no master database or central unit, which gives writing permissions to the database, exists. Instead, every user can write in the database, but all changes are logged indefinitely. If there are conflicting versions, a consensus protocol ensures that all parties agree on one version and continue working with that. In its most known, used and proven form this distributed ledger technology was used to implement a digital currency called Bitcoin. The Bitcoin database is called the “blockchain” since transactions are stored in blocks, and each block uses a hashing algorithm to include information from all previous blocks – a chain.[4] This chain-like structure makes changing previous blocks nearly impossible. The attempt would require tremendous amounts of computing power. Consensus for Bitcoin is reached through proof of work. A significant amount of computing power and time has to be invested to add a block to the blockchain, in other words to write and prolong the decentralised database. The person that supplies this computing power is rewarded with Bitcoins – the money of this digital currency. For the improvement of waste management and a transition to a circular economy, there is a need to track material flows and to pass on data on materials and products in the supply chain. It is hoped that the DLT will be able to solve some of the barriers that arise with these tasks. The hypothesis is that through DLT flows of material and waste can be easily stored and monitored because the data can be made publicly available in a distributed ledger. A product's lifecycle should then be stored in the blockchain for better tracing and more information on the product's history.

[4] While the actual implementation for bitcoins is done using merkle trees, the authors decided to stick to the image of a chain for the sake of simplicity.

So far blockchain has especially seen application in several attempts in the waste management sector to reduce plastics littering and improve plastics recycling (Nicolas, Berg, 2019). Figure 4.4 provides an overview.

Figure 4.4: Exemplary applications of DLT in the waste management sector



Source: Nicolas, Berg, 2019

4.2 State of digitalisation in waste management

This section provides an overview on the application of digital technologies in the waste management sector. The current status of digitalisation of the waste sector in an international context was the topic of a survey of the International Solid Waste Association (ISWA) with about 1000 international experts in the waste management industry. To the question whether *"... the 4th Industrial Revolution will influence the waste and recycling industry"*, 66 % of the respondents answered "yes", 31 % "somewhat yes". Half of these respondents think that the 4th Industrial Revolution will have a great influence, 45% think that it will have some influence. The biggest influence is expected to come from the development of new materials and sensors, with chatbots (62%), fully automated recycling plants (72%) and fully automated sorting plants (80%) named as top 3 innovations. The main investment targets will be apps (47%), new sensors (47%) social media (45%) and Big Data (44%) according to the participants.

Overall, however, there is still a great need for knowledge - only 14% of the experts consulted in this survey say they know "a lot" about the 4th Industrial Revolution, 57% would say they know "something" about it (ISWA, 2017). A subsequent report by ISWA about digitalisation describes best practice examples and drafts further developments (ISWA, 2019).

Many digital technologies have been introduced in the waste management sector, but the field is still quite heterogeneous. While highly competitive private companies and bigger public players seem to adopt these technologies faster, smaller companies and public enterprises are more hesitant or cannot make the necessary investments (ISWA, 2019).

The three areas of communication, waste collection and internal processes have been the main focus of digitalisation up to now. The developments in these fields are discussed separately below. The report will not specifically discuss digitalisation of recycling beyond sorting, landfill and incineration in detail for different reasons. Digital tools for recycling processes of materials obviously exist and many more are being developed, ranging from process automation and quality control to e-commerce platforms for trade. However, the technologies required and employed differ widely, for example, based on the large variety of different materials (plastics, metals, wood, paper, glass, etc.) each of which requires different treatments, has different market characteristics and so forth. The analysis of digital recycling technologies in their entirety would therefore require its own dedicated study and cannot be sufficiently addressed here. Digitalisation in landfills and energy-from-waste (incineration) facilities exist, with some notable examples such as the ReSource International example cited above (drone-based data collection) as well as AI-based services for detection, registration and handling of illegal landfills and littering. In accordance with the priorities defined by the waste hierarchy (recycling should be prioritised over recovery and disposal), an effective use of digital technologies for improving waste management should subsequently and ideally reduce the amount of waste directed to recovery and disposal. For limiting the scope of this study these two least preferred options are not further discussed.

4.2.1 Communication

Communication technology makes up the biggest part of digital solutions already in use in the waste sector. Here the transfer from other sectors is easy because the necessary investment in hardware is relatively low. For municipal waste disposers, communication is important to stay in touch with citizens. For commercial waste businesses, communication with customers is a mandatory and important part especially when tasks such as billing and documentation are included.

One aspect is communication from the waste disposal company to customers or citizens. It includes information on pick-up dates, information on waste separation into different types, bills, and reports on disposed waste. Communication from the citizen or customer to the waste disposal company is needed to schedule pick-ups, change data for ongoing waste contracts, inquire on prices and services, and handle any other type of customer contact initiated by the customer.

Several digital solutions exist to help facilitate and streamline this communication process. They can be subdivided into the following categories (Berg, forthcoming):

- Website – serves above all to display general information on the offered service, prices, etc. When designed as a web-portal, it facilitates the process of contacting the service or changing data needed for service fulfilment by providing appropriate input forms. Municipal services often show information on waste separation, provide information on public collection stations and containers, offer reminder services if a routine pick-up service is scheduled, give information on special waste such as hazardous waste and provide the possibility to report illegal littering or other issues.
- Mobile App – all the information presented on a website can be accessed via a mobile device as well. Additionally, the possibility of individualised apps exists. It allows for an easy personalisation to deliver individual calendars, push-messages for news and important events. Furthermore, the

built-in sensors of mobile handheld devices allow integration of data such as position or the use of functionalities such as QR-Codes, images, or NFC Tags. Dedicated software for business-to-business communication allows for easy creation or modification of jobs, such as collection requests, and facilitates the subsequent documentation and billing tasks if the required information is passed along in or between the digital systems

- Integration in existing apps or websites for public services – If there is a communication solution for other public services already, often waste-related information of public waste services is integrated. This reduces the number of different information access points and increases convenience for citizens.
- Use of proprietary communication apps – third party apps for communication such as WhatsApp, Facebook, Twitter or Instagram are used by some waste companies for public relations purposes or even to communicate with customers. In a ranking of technologies that will have the most impact on solid waste management, social media was ranked 5th place (ISWA, 2017).

Many of these communication solutions need to work with personal data. It is therefore important to consider the data protection legislation – especially GDPR – in an early stage during the design phase of digital solutions.

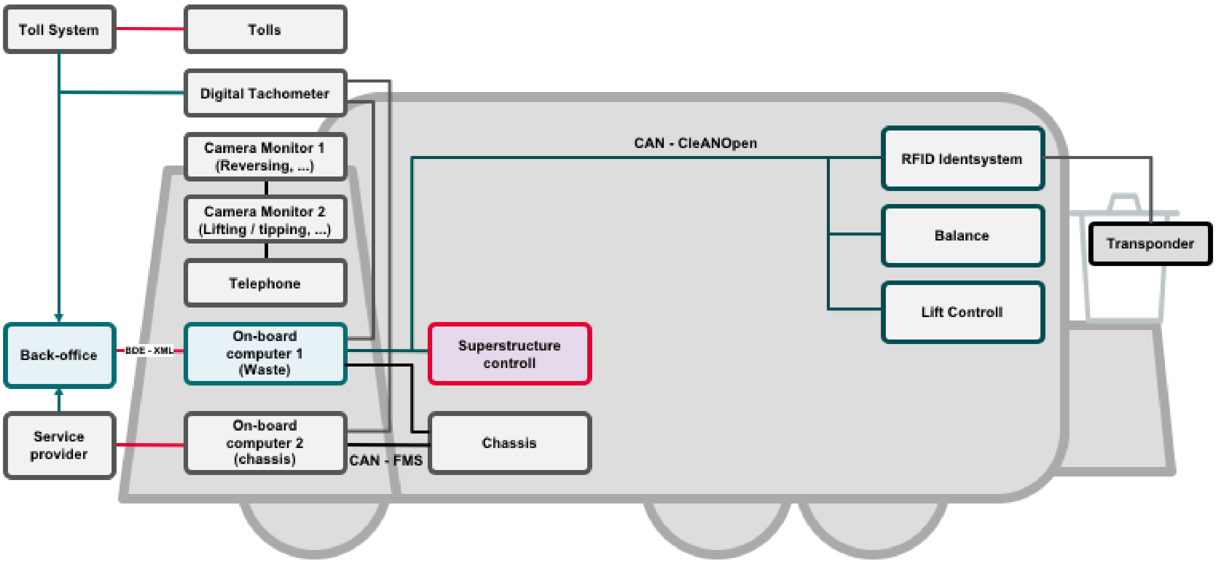
4.2.2 Waste collection

Waste collection is an important part of the waste business, and the digitalisation process is already taking place. Several parts of the waste collection process can be digitalised such as automated documentation, use of sensors in the collection process, routing and the inventory tracking and resource planning.

Collection vehicles can be equipped with sensors, see Figure 4.5. Apart from the standard suite of sensors built into trucks, there are several sensors specific for the waste industry such as a balance checking the weight of the collected waste, RFID sensors for the identification of individual garbage bins or GPS sensors to track the location of the vehicle (Figure 4.5). For the integration of sensors into the refuse collection vehicles' CAN-Bus, the CleANopen standard has been established. It is specified in the EN pr16815:2018 norm. Internal communication for functions such as bin-lifting, measuring or the crane-unit is described here (CiA - CAN in Automation, 2019; Industrial embedded systems, n.d.). A good overview on the topic can be found in a technical overview of two German waste associations (BDE - Bundesverband der deutschen Entsorgungs-, Wasser- und Rohstoffwirtschaft and VKU - Verband Kommunaler Unternehmen, 2016).

Route planning is an integral part of the waste collection process and benefits from digital tools based on geographic information systems (GIS) to optimise routes and save operation time. The routing task was handled manually in the past, nowadays digital tools allow for the optimisation of fixed routes or can include real time data to optimise routes for the current traffic situation. Additional boundary conditions and inputs such as avoidance of schools in opening times or ignoring containers that are serviced less frequently can be taken into account. Individual routes can then be transmitted to the vehicle's navigation hardware to communicate them to the drivers. These routing solutions are applied in the waste collection industry already and are integrated in various software applications. Due to the high costs for running, maintaining and operating the crewed collection vehicles, even minor improvements in the routing can have a fast return of investment (ISWA, 2019).

Figure 4.5: Waste collection vehicles and the integrated digital solutions.



Source: Adapted from a BDE/VKU publication (BDE - Bundesverband der deutschen Entsorgungs-, Wasser- und Rohstoffwirtschaft and VKU - Verband Kommunaler Unternehmen, 2015

4.2.3 Internal processes

In general, no matter what industry, nearly all paper-based processes that concern storing or passing on information are and will be affected by digitalisation. The same is happening in the waste sector. Billing, accounting, controlling, processing of orders, documentation, subcontractor management and many more processes are digitalised. The advantages are obvious: less costs, better storability, better searchability as well as less transfer work and fewer errors if a piece of information is used multiple times. Software solutions exist for all these tasks. There is specialised software for single tasks, and software packages that cover the whole process. Interfaces and compatibility in between software solutions are important aspects to consider and as of yet are not completely developed.

As an example, for hazardous waste that requires a proof of disposal and documentation of the related steps, an electronic waste documentation procedure (“Elektronisches Abfallnachweisverfahren” - eANV) has been established in Germany nearly ten years ago. All parties involved communicate electronically instead of using paper forms, as was the case in the past. These parties can be authorities, disposal companies, collectors, carriers or producers. Linked to the eANV is the obligation to keep an electronic register and use an electronic signature.

Table 4.1 gives an overview of the aforementioned digital solutions applied in the waste management sector.

Table 4.1: Examples of existing applications of digital technologies in waste management

Communication	Waste Collection	Internal processes
Websites	Sensor-equipped vehicles	Billing
Mobile apps	Route planning	Accounting
Integration in other services	Resource planning	Controlling
Third party social media apps	Inventory tracking	Processing of orders
	Documentation	Documentation

4.3 Applications and case studies of digital technologies in waste management

In this section several case studies, some of them existing case studies (voluntarily anonymized) are presented that show how digital technologies are applied for various tasks in the waste management sector. Each case study is presented in a standardised form (factsheet) to allow getting a quick overview and for better comparability.

<table>
<tr><th colspan="2">Robotic Waste Recycling System</th></tr>
<tr><td colspan="2">● AI System that can be trained to sort a waste stream based on camera and Near-infrared (NIR) input data
● waste is supplied on a belt and then sorted by an x-y-z axis robotic system into different containers
● positive sorting for several fractions</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>● sensors
● data analytics
● AI-image classification
● robotics</td><td>● broad-band internet connection for cloud access</td></tr>
<tr><th>Benefits for waste management</th><th>Pros and Cons</th></tr>
<tr><td>The technology is able to adapt to new waste streams fast and allows for high purity sorting of this waste into multiple fractions. This improved purity leads to high-grade secondary material and less downcycling in the recycling process.</td><td>Pro
● Purity of > 90%, continuous improvement through on-the-fly training
● can pick objects up to 30 kg

Con
● slow belt speed resulting in low throughput compared to established technologies (two-armed version 4000 pics/hr)</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>● image classification is state of the art technology offered by various companies
● there are different competitors in the waste sector
● pick-and-place robots are state of the art technology for example in the food industry</td><td>● several robots running</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>● can be adapted to various items and materials
● probably most suited for construction and demolition waste</td><td>● expert interview
● own research projects</td></tr>
</table>

<table>
<tr><th colspan="2">AI based sorting technology for plastic waste</th></tr>
<tr><td colspan="2">Add-on to existing sorting technology, plug-in in existing sorting lines
improves sorting accuracy by providing additional features for the classification algorithm
is trained using large amounts of sample data
in the actual stage negative sorting of PE silicone cartridges and cartridges of 2K adhesives</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>sensors
data analytics
AI-image classification
automation</td><td>existing sorting infrastructure as a basis for add-on
sample Data
incentives for high purity sorting</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The technology allows to detect impurities that could otherwise not be detected. The rejected substances, like silicone in PE cartridges, can have a negative effect on recyclate quality even if only low amounts are present.</td><td>Pro
rejection of otherwise undetectable impurities
high throughput
Con
add-on, not replacing existing technology
additional costs</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>image classification as underlying technology is offered by various companies</td><td>commercial products exist</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>currently negative sorting of plastic waste
easy adoption to other waste streams</td><td>company homepages</td></tr>
</table>

<table>
<tr><th colspan="2">AI-based litter identification[5]</th></tr>
<tr><td colspan="2">App for mobile devices that provides citizens with the possibility a picture of illegally disposed waste and report it.
the picture and the GPS-coordinates of the littered place are submitted. An AI system classifies the pictures in order to relay it to the concerning person in charge</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>mobile device including camera and GPS sensor
data analytics
AI-image classification</td><td>citizens using smartphones</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The technology reduces the human labour that is needed to handle the incoming reports on illegal littering. It serves to prepare the right removal actions beforehand.</td><td>Pro
less human labour
cost reduction
Con
none</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>image classification is state of the art technology offered by various other companies
the use of sensors in mobile devices is state of the art
the combination and adaption to this specific task is not known to be offered by any other service</td><td>in use by a German municipal service</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>illegal littering</td><td>Berg et al., forthcoming</td></tr>
</table>

[5] A similar representation was published in Berg et al. (forthcoming).

<table>
<tr><th colspan="2">Autonomous refuse truck for waste collection</th></tr>
<tr><td colspan="2">reversing waste collection trucks are a major source of accidents
in general, it is tried to avoid reversing but if necessary, the autonomous driving system can take over or support to minimize accidents and casualties
for normal collection, skilled drivers and co-drivers are needed, but this technology allows less experienced personnel and single crewed driving
collection personnel can walk alongside the autonomous truck when emptying bins which means less getting in and out of the truck, a potential health hazard and source of accidents</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>sensors
data analytics
autonomous driving</td><td>special equipped refuse truck</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The use of autonomous driving for waste collection can be applied to overcome the labor shortage in the waste sector in some regions by reducing the necessary crew for a waste collection truck. Additionally, there might be cost benefits associated with the technology freeing up budget for other important tasks.</td><td>Pro
potential to increase safety for the waste collection process
lead time for bin emptying trash bin is reduced by about 30 seconds per bin because of reversing instead of normal driving
improved fuel efficiency and less wear on truck through driving software
data collection on traffic situations allows prediction in the future
Con
high investment costs
legislation is not adapted to the technology so far</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>autonomous driving is implemented by various companies. However, only one application to the waste collection sector is known so far.</td><td>system is being tested for 5 years
no planned date for commercial availability
similar technology is applied in mining trucks</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>all waste types with street side collection</td><td>Product homepage
ISWA Report (ISWA, 2019)</td></tr>
</table>

<table>
<tr><th colspan="2">Automated vacuum collection[6]</th></tr>
<tr><td colspan="2">different household waste types are collected in coloured bags at collection sites in the streets
a subterranean tube system uses vacuum to suck the bags to a central point where they can be collected easily
an RFID identification system coupled with a scale is used to gather real time data on the waste volumes
the manufacturer claims that this can be used to change user behaviour and improve recycling rates</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>sensors
data analytics</td><td>a dedicated infrastructure is needed</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The system has the potential to lower traffic impact of waste collection and allow to design urban quarters without needing to take into account the respective demands. Possibly an improvement in waste volumes can be achieved</td><td>Pro
easy collection at central sites
real time data on waste volumes and types
Con
easy clogging
difficult maintenance work
difficult retrofitting in existing urban areas</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>the basic vacuum collection technology is in use in different locations
a system including RFID identification and weighing of the waste to create real time data with the aim of changing behaviours is not known by any other manufacturer</td><td>the underlying technology is proven - several tube-based waste collection systems exist – about 600 systems worldwide and 3 million connected people</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>household waste</td><td>Product homepage
ISWA Report (ISWA, 2019)
Berg et al., forthcoming</td></tr>
</table>

[6] A similar representation was published in Berg et al. (forthcoming).

Bin sensors[7]	
- sensors collect vibration data from waste containers - analysis and real-time visualisation of containers levels to improve efficiency in waste logistics - data analysed with AI in the analytics platform	
Underlying Technologies	Requirements and preconditions
- Sensors - Data analytics - AI algorithms - Cloud computing	broad-band internet connection for cloud access
Benefits to waste management	Pros and Cons
Improved logistics through optimisation of waste collection routes reducing unnecessary traffic, subsequently air pollution as well as associated costs.	Pro - Energy self-sufficient - Easy installation (attached to the container in 3 minutes) Con - Risks of manipulation and systems failure - Risks of data loss
Similar applications	Development stage
- Various providers exist - In addition to the fill-level, the bin sensor collects temperature data for enabling timely reactions to incident e.g. fire-alarms if burning - Using RFID transponders and GPS identification system, solutions can also be used for PAYT charges (ISWA, 2019)	About 1000 glass containers equipped in different municipalities in Germany
Applicable waste streams	Sources
- Applicable to all types of containers - Launched on glass containers but currently under development for additional waste streams such as textile or construction and demolition.	- Product homepage - Berg et al., forthcoming

[7] A similar representation was published in Berg et al. (forthcoming).

<table>
<tr><th colspan="2">Software as a Service - Mobile application</th></tr>
<tr><td colspan="2">Mobile application for on-demand waste collection
Digital marketplace (auction-like system) that puts a network of waste collectors in contact with (mostly commercial) customers (caterers, SMEs, hotels, etc.)</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>Cloud computing
Data analytics
Automation</td><td>Network of waste collectors</td></tr>
<tr><th>Benefits to waste management</th><th>Pros and Cons</th></tr>
<tr><td>This application aims to reduce waste collection costs for businesses (orders are made only when needed). In addition to an increased convenience for these businesses, traceability along the waste recycling value chain is facilitated. The revenues of recovered materials are shared with the commercial waste generators. This could also be an incentive for improving the quality of waste collected.</td><td>Pro
Reduction of collection costs by reducing the number of pick-up
Facilitate customers sustainability reporting
Con
Competition between current waste collectors and independent local haulers</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>Apps exist that enable customers to promptly order waste collection services, and interact with waste operators online. Simalrly, another solution allows commercial businesses from different sectors – such as construction, the automobile industry, or food retail – to make individual requests and compare various offers of various waste disposers.</td><td>Network of 5 000 waste collection businesses
Expanding beyond US, for instance partnering with European firms</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>Mainly commercial waste</td><td>Open Resource, 2017
Company Homepages</td></tr>
</table>

Software as a Service - Intelligent Waste Transport Optimisation	
• Real time-based automatic scheduling for waste transport planning optimisation • The solution encompasses fleet management, route planning and optimisation and routing services and is delivered as an integrated part of the service provider's platform or connects to third party ERP systems. • The master routes are planned and optimised in the route planning system based on recurring customer visits. The master routes are then automatically transferred to the Fleet Planner, with which both the operational planning and the actual implementation are managed.	
Underlying Technologies	Requirements and preconditions
• Cloud computing • Sensors • AI • Data analytics	• Customer fleet of vehicles • Customer's involvement for generating data
Benefits to waste management	Pros and Cons
Increased efficiency in waste collection operations, reduction in number of vehicles needed reducing associated transport emissions.	Pro • Customer cost savings and better services • Decrease in time spent on planning and administration Con • /
Similar applications	Development stage
Various provider exist	• Implemented solution. Responsible for collection, administration and deposits for 2,700 stores around Sweden, for instance implemented for optimizing the transportation planning of deposit-refund systems for cans and bottles.
Applicable waste streams	Sources
• All waste types	• company homepage • ISWA Report (ISWA, 2019)

<table>
<tr><th colspan="2">AI Chatbot service</th></tr>
<tr><td colspan="2">AI Systems trained to answer citizen’s questions e.g.for a proper separate collection of waste</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>AI-voice recognition, image classification
Data analytics
Cloud-computing</td><td>broad-band internet connection for cloud access</td></tr>
<tr><th>Benefits to waste management</th><th>Pros and Cons</th></tr>
<tr><td>Answers provided by the chatbot aim at e.g.
improving efficiency in service provision to citizens/customers e g. in answering frequently asked questions,
improving the quality of waste collection by support of separation.</td><td>Pro
Accuracy of answers provided usually high
Improvement of services
Increased awareness for citizens
Con
Some customers reject talking to machines
Waste managers sometimes fear to lose contact to their customers</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>Various providers exist</td><td>Chatbots are a market ready technology</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>Chatbots exist for different users (e.g. municipal waste managers) and are applicable to different waste streams.</td><td>Various company homepages
Berg et al. (forthcoming)</td></tr>
</table>

5 Digital technologies as enablers for the advancement of the current European waste management regime

5.1 Improvement of waste collection and treatment

The accelerators and inhibitors presented for waste collection and treatment in chapter 3, define the field where improvement through digitalisation occurs or is expected to take place. The technologies applied in this field, largely consist of combinations of the technologies presented in section 4.1 (also: Berg et al., forthcoming).

Waste collection systems and their operation can make up an important share of the cost for disposal and recycling and are quite labour intensive. For example, shares of 40 to 65 % of the total operational costs were determined for the collection of paper and packaging waste from households in four case studies in different European countries (van Leeuwen et al., 2020, p. 104). Several aspects of collection are being transformed by digitalisation, especially **logistics**, the process of organising, planning, scheduling and dispatching the tasks, personnel and vehicles. Here, digital tools offer the possibility of enhancing the process by storing, processing, analysing and optimising all necessary information and presenting it in an appropriate way. The ability to search data or to put it into context enhances the overall performance of the dispatching person as well as the performance of the concerned tasks. Information generated during the collection process, for example on temporal progress or incidents, can be fed back into the system. With this information another feature of digital systems comes into play to improve operations. Where the amount of information and complexity grows too large to be handled by humans, optimisation algorithms can help to find the most suitable options for allocating resources, such as work force or vehicles. Important technologies are telematics, including routing systems, navigation and vehicle tracking software, Enterprise Resource Planning (ERP) systems and similar. The resulting improvements mostly find expression in an increase in efficiency. If upcoming technologies such as IoT with applications like smart bins, robotics for semi-autonomous waste collection vehicles or AI for waste prediction are considered, there is substantial room to improve the waste collection process in the future and to align it with the needs of a circular economy. For example, a more flexible reaction to changing waste patterns and targets, or the implementation of on-demand and customised services can be facilitated (ISWA, 2019, p. 24).

Another part of waste collection is the process of **documentation, informing and billing**. Here, the ongoing switch from paper-based administration systems to digital systems as seen in other industries will further increase efficiency and information flow for processes. Technologies to be named are digital ID tags for waste bins and containers, digital order processing, digital billing and payment, digital user interfaces for communication and information update, as well as interconnection of other relevant governmental databases to public waste collection providers. If these digital technologies are applied in the documentation processes, they can be used for gathering public waste related data. Turned into valuable information by data analytics, they can support a circular economy by "a better understanding of the spatial and temporal patterns of waste generation" (ISWA, 2019, p. 24). Additionally, the possibility of collecting many single data points instead of just reporting cumulative values, can provide further insights for authorities.

Pay as you throw systems become more feasible using digital identification and billing techniques. They are deployed in different locations over Europe (ISWA, 2019, p. 24). These systems allow for a "fair" billing scheme by allocating costs proportional to the amount of waste generated. Nevertheless, it was shown that there are negative effects through avoidance such as increased illegal littering, use of public bins and "waste tourism" to bordering regions with traditional billing schemes (Kinnaman, 2009).

Furthermore, an improvement in **communication** with customers and the public can be expected when using digital communication channels. Examples are on-demand and personalised information, the possibility to conveniently change personal data through digital interfaces and push-messages through social-media channels. An online based complaint management allows to draw attention to problems timely (ISWA, 2019, p. 24). Further improvement is envisioned in the form of nudging through tailored messaging on a personal level - for example appreciation for waste savings or good separation behaviour can be implemented as well as notifications if separation behaviour was not satisfactory. These solutions are intersecting with the field of waste prevention.

Improvements in the automated **treatment and handling** of waste that substitute human labour are expected to be introduced. A driver of this development is the cost pressure elaborated in chapter 3. One important field of application is the **sorting** process as a prerequisite for recycling. At present, sorting is usually carried out up to a certain purity level, although better sorting would be possible. However, it is then not economically feasible or necessary for the intended use. Digital technologies that increase the cost efficiency and/or precision of the process will enable better sorting at lower prices and thus improve the range of secondary material quality available to production processes. AI supported robotic sorters are a technology in fast development. Another often-discussed approach is the labelling of products using watermarks, QR codes or other kinds of digitally readable markers. Including information on material composition of the product, these could facilitate the sorting process and enhance the recyclate quality. Accompanying data collection and analysis allows for deep insights into the automated processes and lay the foundation for further improvement. For example, an analysis of the input stream could be used to predict daily and seasonal effects and adjust the sorting lines accordingly. Also, a quick response to changing targets or even market prices is conceivable (ISWA, 2019, p. 36).

Table 5.1 summarises established and emerging digital technologies applied to waste collection and waste treatment, as described in the preceding section.

Table 5.1; Established and emerging digital technologies for waste collection and waste treatment.

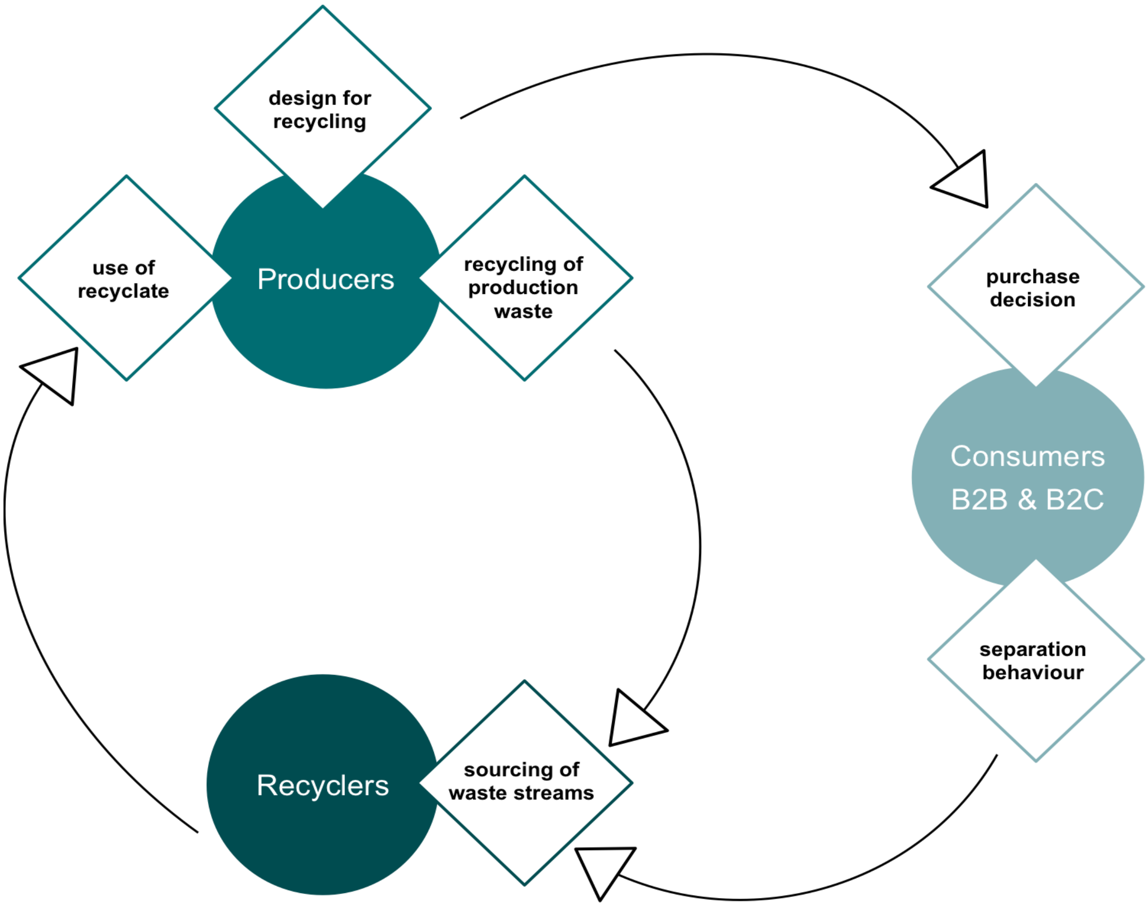
	Collection & Communication				
	logistics	**administration**	**communication**	**sorting**	**recycling**
Established	telematics Route optimization, navigation, vehicle tracking, Smart bins, IoT	ID tags, order processing, digital billing, digital payment, ERP systems, paperless office, interoperability	complaint management, digital interfaces, on-demand and personalised information, electronic services	AI-based recognition processes, sensor-based material identification	Process controls, sensoring (e.g. spectrometry) Trading platforms Material matching
Emerging	robotics, autonomous vehicles	data analytics	Nudging, augmented reality, chat-bots	digital labelling, tracking and tracing, robotics Advanced data analytics	Electronic quality assurance systems, automated data transfer for increased trade and market transparency (digital product passport), data analytics

5.2 Improvement of the recycling chain

The recycling sector as one of the key sectors for a circular economy (as further introduced in Chapter 7) has made progress over the past decades. However, research shows that in many industries a major share of materials is still not being recycled. Digital technologies provide the chance to considerably advance the development of recycling and to unlock new possibilities. This section presents the possible improvements from an actor-oriented view with the main actors being producers, consumers and recyclers. The critical actions that need to be undertaken to enable a circular economy by these actors can be summarised as follows (see Figure 5.1):

- producers: design for recycling, use of recyclates and recycling of production waste
- consumers: improving separation behaviour and purchase decisions
- recyclers: improving the sourcing of suitable waste-streams

Figure 5.1: Critical actions of producers, consumers and recyclers with respect to recycling.



There are several barriers that currently hold these actors back from implementing such critical actions. Many of these can be addressed by digital technologies as presented in the following paragraphs.

Producers

The design of products and materials is a crucial factor for the cost of recycling and thus for the competitiveness of recyclates (European Environment Agency, 2019b, p. 215). However, one potential barrier for the design for recycling is the lack of know-how of product designers and construction engineers on what the best material options are and how they can be combined and compiled to yield a well-recyclable, small-footprint product. Here, the possibility of digitally distributing knowledge can be leveraged. Several universities offer online courses free of charge that dive into these topics such as: "Engineering Design for a circular economy" or "Sustainable Packaging in a Circular Economy" by TU Delft and "Circular Fashion: Design, Science and Value in a sustainable clothing industry" or "Circular Economy: An Interdisciplinary Approach" by the University of Wageningen. The Round Table "Ecodesign of Plastics Packaging" (IK Industrievereinigung Kunststoffverpackungen e.V., 2020), an industrial initiative, provides guidelines and tools for implementing design for recycling approaches. Apps like "Idemat" offer product designers an easy possibility to compare the LCA-based impact of the materials they use.

As the costs and benefits of design for recycling are unevenly distributed among producers and recyclers, there is a need to incentivise collaboration across the value chain. Advancing the implementation of extended producer responsibility (EPR) schemes could foster such collaboration. As mentioned in section 3.1, digital technologies can play a crucial role in this context.

One example for a corresponding legislation is the German Packaging Act ("Verpackungsgesetz"). It supports design for recycling by discounts on the recycling fee that has to be paid for every packaged item sold, and is used to pay the recycling industry to recycle this packaging waste. Monitoring and documentation necessary for the implementation of this legislation rely heavily on digital technologies and would not be manageable without them.

Together, these different approaches enable better design for recycling and thus a higher quality of the waste stream.

Another critical action, the use of recyclates for products, can be facilitated by digital technologies. Wilts and Berg have described the requirements for a higher recyclate use (Wilts and Berg, 2017). The main points are the possibility to implement a proof of quality, lowering transaction as well as search costs, and enabling a steady supply of recyclates through better matching of supply and demand. All these aspects can be addressed digitally which would lower some of the barriers for producers to use recyclate for their products. For example, digital technologies can help by tracking and proving recyclate quality at a highly granular level, e.g. for every single lot. Additionally, if the quality can be matched to the corresponding product through better searchability, this results not only in more recyclate being used, but also in less downcycling.

Recycling of production waste is another way with which producers can support a circular economy. The related barriers are strongly depending on the actual use case. However, in settings where recycling is carried out by external businesses, the same barriers and solutions as presented above for the use of recyclate apply. Digital solutions may enable the information flow between manufacturers and recyclers that is necessary for a high-quality recycling of production residues, as currently examined in the Interreg-funded project "Di-Plast" for the plastic industry in Northwestern Europe.

Consumers

A critical action on the consumer side is to improve separation behaviour (EPC - European Policy Centre, 2019, p. 12). Here, digital communication technologies and tools can be used, acting in two different ways. On the one hand, the knowledge needed to separate waste correctly can be provided easily using digital tools. Barcode scanning apps that explain how to recycle a specific product or packaging are one example. Similarly, in business environments it is possible to retrieve information about the sorting of common waste items on handheld devices or the like. On the other hand, it is important to enhance the motivation of consumers for making recycling efforts by raising awareness for the problem and showing how each person can contribute to the solution. Here, communication in social media channels can be used.

Another critical consumer action is the purchasing decision. If recycled content and recyclability play an important part in choosing a product, this can leverage more use of recyclate and design for recyclability on the producers' side. The technology used by apps like CodeCheck, that present information about the sustainability of products to the customer when scanning their barcode, could also be applied to recycling-related information. Another group of consumers that have a huge leverage are public authorities and their public procurement policies. Here, the barrier usually is a lack of knowledge or the distrust in recycled materials, which could in principle be addressed by digital information and communication measures, although there are no examples of that kind so far.

Recyclers

On the recycler side, a critical action is improving the sourcing of waste streams, which can be supported by waste-trading platforms such as those available for scrap-metal or plastic waste (EPC - European Policy Centre, 2019, p. 9). As mentioned above, search and transaction costs are lowered drastically in this way, improving the price competitiveness of recycled materials compared with virgin materials. Moreover, faster and more transparent information about available quantities of suitable waste streams can facilitate more stable recycling markets (ISWA, 2019, p. 36). Additionally, better reporting on quality could be forced by the waste-trading platforms as the possibility to easily compare different offers turns additional information on waste quality into an added value. The introduction of material passports could help providing such information in a reliable and transparent way (ISWA, 2019, p. 36).

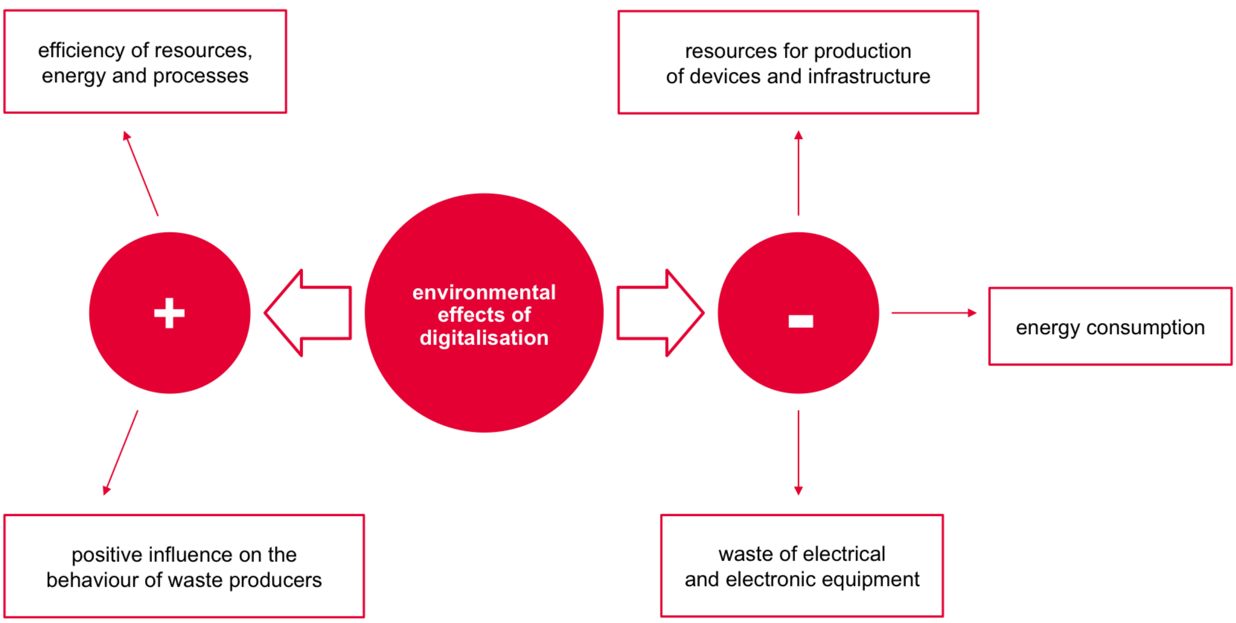
6 External effects of digitalisation in the waste management sector

The following sections present existing and emerging external effects from digitalisation in the waste management sector now and in future. Some of those external effects are the results of rebound effects: an increase in consumption which may occur as an unintended side-effect of the introduction of policy, market and/or technology interventions aimed at environmental efficiency improvements, and which is caused by behavioural and/or other systemic responses to the interventions, in particular where the efficiency gains come with reduced costs (Maxwell et al., 2011). Derived from the task given, the effects are structured along the dimensions of environmental, social and economic effects, hence covering the full area of sustainability.

6.1 Environmental effects

The digital transformation has so far shown ambiguous effects on the environment. Adverse effects concern excessive use of energy and resources caused by certain technologies and processes (streaming, blockchain applications,…). On the other hand, digital technologies have allowed for vast efficiency gains in terms of energy, resource, time and cost reduction in other areas, e.g. through digitally improved project and process design. Both effects imply a need for high scrutiny regarding the impact of digital technologies in the future and an active management of the digital transformation on the side of policy makers. Positive and negative external effects caused by digital technologies in the waste management sector are discussed below. Figure 6.1 summarises the main points.

Figure 6.1: Positive and negative environmental effects of digitalisation.



The adverse environmental impact of digital technology can mainly be divided into three fields: the resources needed for the production of its devices, the energy consumption during its use and the generation of Waste of Electrical and Electronic Equipment (WEEE). While there is only limited data on resource use, it is clear that the environmental burden of digitalisation is not neglectable. For example, the electricity used globally for the production and the operation of consumer devices (including entertainment electronics such as TV), network infrastructure and data centres is expected to reach about

10 % of the global electricity usage in 2020 and to rise up to 20 % in 2030 (Andrae and Edler, 2015). Estimations for the global carbon footprint of information and communication technology (ICT) in 2030 range from about 1.3 Gt to 2.1 Gt CO_2 (Andrae, 2020), representing about 4-5 % of the global carbon emissions CO_2. In 2016, about 44.7 Mt of E-waste was generated, of which only 20 % was collected and properly recycled (Baldé et al., 2017).

On the other hand, increases in process efficiency through digital applications or the transformation of physical (e.g. paper-based) systems into digital ones can potentially be environmentally advantageous. Another field where digital technologies already have an impact and will likely play an important role is monitoring and tracking. Even with strict pro-environmental legislation, it is often difficult to control and enforce that legislation. Here, automated digital monitoring and reporting of emissions, immissions and material flows can facilitate, enable and intensify law enforcement.

While, to the knowledge of the authors, there are no studies quantifying the environmental effects of digitalisation for the waste management sector, the potential can be assessed by regarding analogous numbers. The Global e-Sustainability Initiative (GeSI), a partnership of ICT companies and industry associations, estimates the global greenhouse gas abatement potential of ICT for 2030 to be 12.1 Gt CO_2e, with the biggest potentials in manufacturing (22 % of total abatement potential), agriculture (17 %), buildings (16 %), energy (15 %) and logistics (10 %). When considering rebound effects, the abatement potential is revised downwards to 10.7 Gt (GeSI - Global e-Sustainability Initiative, 2015). Even though these numbers are based on a bottom-up model approach with many assumptions which are not reported in detail and have thus to be treated with caution, they hold the promise to save a multiple of the ICT's own emissions. To get an idea of the order of magnitude for the potential benefits for the waste management sector, it might be instructive to look at a similar sector: For transportation, the International Energy Agency expects a 22.6 % reduction of energy use in road freight from 2015 to 2050 through digital technologies (IEA - International Energy Agency, 2017, p. 38). The examples for underlying technological solutions mentioned in the report (real time route optimisation, on-board monitoring for eco-driving performance, vehicle connectivity, data sharing across the supply chain) are in principle also applicable to and to some extent already applied in waste management.

6.2 Economic effects

6.2.1 Effects on Companies

The use of digital technologies comes with a change in cost structure. While efficiency is increased resulting in a lower OPEX (operational costs such as labour), usually the investment costs for these digital solutions are higher than for their traditional alternatives resulting in higher CAPEX (cost of capital). All in all, a shift from OPEX to CAPEX can be observed. This favours bigger players that can raise the required money and can be a problem for public companies where large investment costs can be a political issue.

This shift in cost structure can be counteracted by employing as-a-service or pay-per-use models that are widely available in the digital sector.

Workforce characteristics will likely be changing through the change in skill sets required to operate digital technologies and potentially need less (unskilled) labour due to automation. Additionally, faster changing product cycles make a continuous training necessary.

Private waste companies are more forced to digitalise their operations as shown in chapter 3. This pressure is less for public waste companies since there is less competition. So, while the aforementioned effects apply to both types, they will likely be more pronounced in private companies.

6.2.2 Effects on business models

There are several business models emerging or already established in the course of digitalisation of the waste sector. Additionally, it is expected that new business models will be created (again mentioned in section 7.2.4). Implications vary substantially from business model to business model - a range of exemplary cases and their implications are presented here.

There are several businesses that are trying to adopt the **digital platform model** to waste and recycling businesses. Examples are *plastship.com* or *cirplus.com*. The aim of both is to be the go-to location for, for example plastic waste. Implications are diverse. Firstly, we can assume that easy matching of supply and demand will contribute to increasing overall recycling rates. Secondly these portals would have the market power to enforce quality standards or the supply of material information from the business side. If this is the case, an improvement in material quality and thus of recycling would result.

Several companies are offering **software suits** that address the specific needs of waste companies like container management, vehicle tracking or else. *Recyclingmonitor.de* is one example that uses the connectivity and sensors built into modern handheld mobile devices to carry out these tasks. While these allow for various improvements, their functionality and security have to be ensured.

Business analytics applications for the waste management sector are creating an added value by putting the available data into perspective. Examples are AMCS (AMCS Group, 2020) or TouchStar (TouchStar Technologies Ltd., 2020). Solutions for an automatic measurement of fill levels of containers and transmission of the data that can be used for optimisation, have been presented in the first part. **Identification systems** on containers which restricted access to a certain user group are offered by emz Hanauer (EMZ, 2020). While this would be possible with an analogue key system as well, the added value consists of usage data being collected and transmitted instantly, and possible programming, for example to enforce opening hours reducing nightly noise pollution.

It is expected that future business models will build on the increase in available data and digital infrastructure.

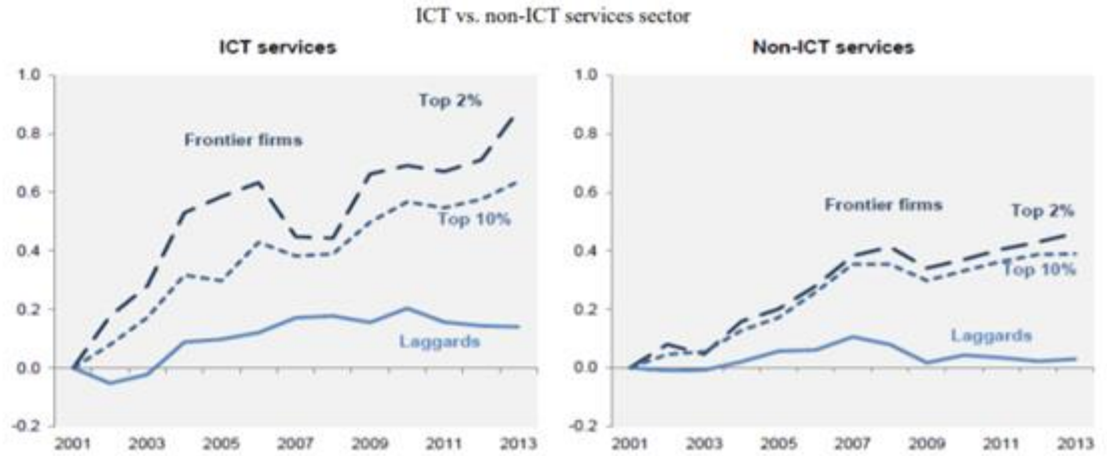
6.2.3 Effects on productivity and the labour market

As mentioned in section 2.1, there is a consensus that the digital transformation has enormous growth potential. The potential contribution to European GDP from achieving a fully functioning Digital Single Market (Digital Europe Programme, 2019) has been estimated at 415 billion euros. However, as for most digital technologies discussed within the scope of this study, which are still moving from the lab to adoption, it is not feasible yet to quantify their effects at a macro-economic level (Katz, R., 2017). Based on this distinction between technological innovation, diffusion and economic effects, it is currently considered difficult to forecast the speed at which these digital technologies will undergo adoption, especially when targeting one specific sector.

Digital transformation of our economies indeed holds the promise of improving productivity performance by enabling innovation and reducing the costs of a range of business processes. But despite the rapid rise of digital technologies starting in the mid-1990's, aggregate productivity growth has slowed over the past decade or so, sparking a lively debate about the potential for digital technologies to boost productivity.

However, according to the OECD and shown with Figure 6.2: "*Looking behind the aggregate and sectoral statistics, micro-level studies reveal that the aggregate productivity slowdown masks a widening performance gap between more productive and less productive firms, especially in ICT-intensive sectors. This divergence is not just driven by frontier firms pushing the productivity frontier out, but also by the stagnating productivity of laggard firms related to the limited capabilities of, or lack of incentives for, such firms to adopt best practices. Together, these signs illustrate that the main source of the productivity slowdown is not so much a slowing of innovation by the most globally advanced firms, but uneven uptake and diffusion of these innovations throughout the economy*" (OECD, 2017b).

Figure 6.2 Divergence in multi-factor productivity growth between more productive and less productive firms.



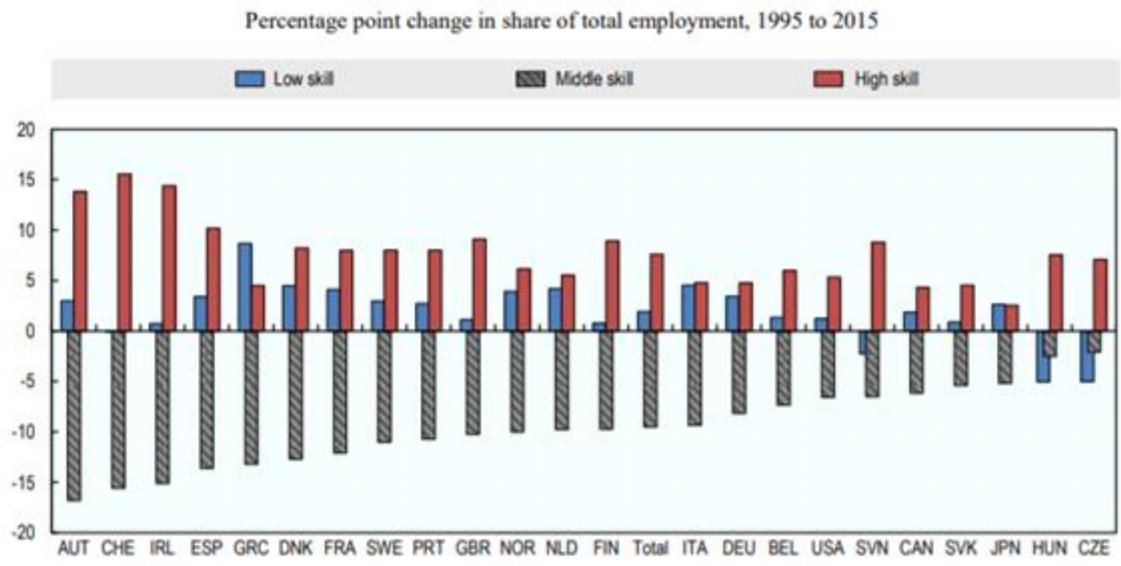
Source: Copied from OECD, 2017b

Once mass adoption will occur, it is reasonable to conclude that the economic effects will be significant. One of them targets the labour market: while new technologies create opportunities for businesses, workers and citizens to engage in economic activity, these technologies are also likely to displace workers doing specific tasks and may further increase existing gaps in access and use, resulting in new digital divides and greater inequality.

Not only targeting the waste sector and EEA Member States, recent OECD estimates suggest that on average 14% of jobs are at a high risk of automation in the next 15-20 years. Another 31% of jobs are at risk of significant change in terms of task content as a result of automation. Those estimates also explain that new jobs will be created, and there is no evidence that digital transformation has been associated with net job losses overall.

However, those new jobs are not the same as those that are lost, and polarisation in the labour market is a concern. High-skilled workers have thus far tended to benefit relatively more from technological change, while the share of employment in middle-skilled jobs has decreased. Going forward, low-skilled workers are most at risk of losing their jobs and being left behind, see Figure 6.3.

Figure 6.3: Decrease of middle skilled between 1995 and 2015 for different countries.



Source: copied from OECD, 2017c

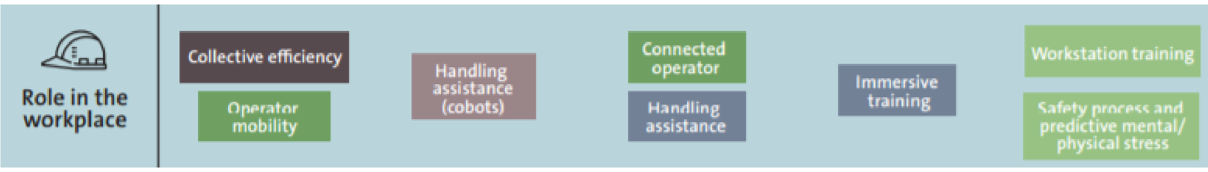
6.3 Social effects

6.3.1 A new role for workers

Still depending on the speed of adoption of digital technologies mentioned above, major changes in the division of work between machines and people will occur with high certainty. Whereas automation supposes a transfer of knowledge and expertise from operator to system, robotics provide operators with assistance from a robot they can interact with (Messenger, 2018). Today, this involves pooling skill sets between people and machines. At a sorting centre, tele-operated sorting enables operators to work from a touch-screen in a cabin, away from the sorting belt, after an initial fully automated sorting operation. In this way, the dirty and potentially unhealthy process of sorting can be designed to be both safer and healthier. However, sorting certain waste streams, such as plastic bags, still demands a combination of actions in a three-step process: hand sorting for large film plastic, ballistic separator for other films, and a final optical sorting.

As discussed in section 6.2.3 and shown in Figure 6.3, polarisation is a concern in the labour market. These changes, combined with rapid changes of economic models, destabilize employees' skills bases. Transformations impacting employment types and how they are organised, will lead to more frequent changes of jobs and task. Training methods will also evolve towards a peer-to-peer model, via platforms or augmented reality, allowing people to acquire the skills they need as and when they need them. However, not all employees within an organisation will necessarily be treated equally, if only because some will be digital natives and others not. People occupying the most-impacted posts will have the greatest need for upskilling, but they risk being disadvantaged in favour of those occupying roles judged strategically important. Those transformations are illustrated in Figure 6.4.

Figure 6.4: Roles in digitalised workplaces.



Source: Copied from Phung, C., 2019

Despite the numerous advantages and facilitations that digital technologies imply, resistance from employers against their introduction can be observed (Berg et al., forthcoming). There are three main concerns

- surveillance - as every work step in a digitalised workplace creates data, it is much easier to use this data to track, analyse, compare and judge the performance of each worker. Who is driving the waste trucks too aggressively/working too slowly? What team constellations are working most efficiently? What tasks are employees spending their time on? And so on.. This leads to rejection in some parts of the workforce;
- training - digital technologies enable faster innovation cycles and fast progression of updates, features and technologies. This requires employees to adapt to all of these changes and keep themselves up to date through ongoing training. This is not always viewed as positive;
- replacement - parts of the workforce see digitalisation and automation as a threat since it can replace existing jobs.

An issue that may need attention in this regard is that of informal labour. In many countries, also in Europe, a considerable amount of people are working informally in the waste sector, especially in the area of sorting, and often under difficult conditions and conflicting with existing laws and regulations. It is very likely that much of this informal work will be rendered unnecessary should the digital transformation of the waste sector be pursued to a wide extent. For example, electronically improved sorting and recycling may leave very few waste streams that contain valuable sources for informal sorting and sales. The extent to which this may occur could not be analysed in this report due to restrictions in time and data, but may require further investigation in the future.

6.3.2 Citizens & Consumers

Digitalisation of waste management activities will have clear social effects on workers of the waste sector, but it is also essential to mention its effects on citizens and consumers. While it has been mentioned that the use of certain digital technologies can help in better informing consumer choices or facilitate citizens' separation behaviour, this transition can also affect their role in the waste sector. Societal acceptance by citizens is essential for enabling high quality recycling (Vanderreydt et al., 2019), but encouraging them to use and collect data can convert citizens into active participants of a more digital economy and co-creators of knowledge and evidence (Hedberg and Sipka, 2020). At the same time, protection of personal data is of great importance.

Participation and individuality have been identified as core values for a sustainable digitalisation for citizens (Burgard, 2018). "Participation" relates to establishing minimum standards for economic and political participation while "individuality" stresses the value of distinct individuals as a resource for well-being and quality of life. For the waste and waste management sector, participation can be implemented by transparent and accessible data concerning waste generation and costs for its collection and treatment, especially if these operations are carried out by public actors or are of public interest because of potential health and ecological hazards. Individuality can be implemented for example by individual collection calendars, collection-on-demand or pay-per-use models.

7 A broader perspective: digitalisation for the circular economy

The following chapter widens the scope from the use of digital technologies in waste management to their use and enabling role in a more comprehensive circular economy, starting off with looking at recent developments of the political landscape. The authors see this broadening as important, since in a future circular economy, that is highly integrated through digital technologies, the waste sector will need to be integrated as well to fulfil its tasks in such a system.

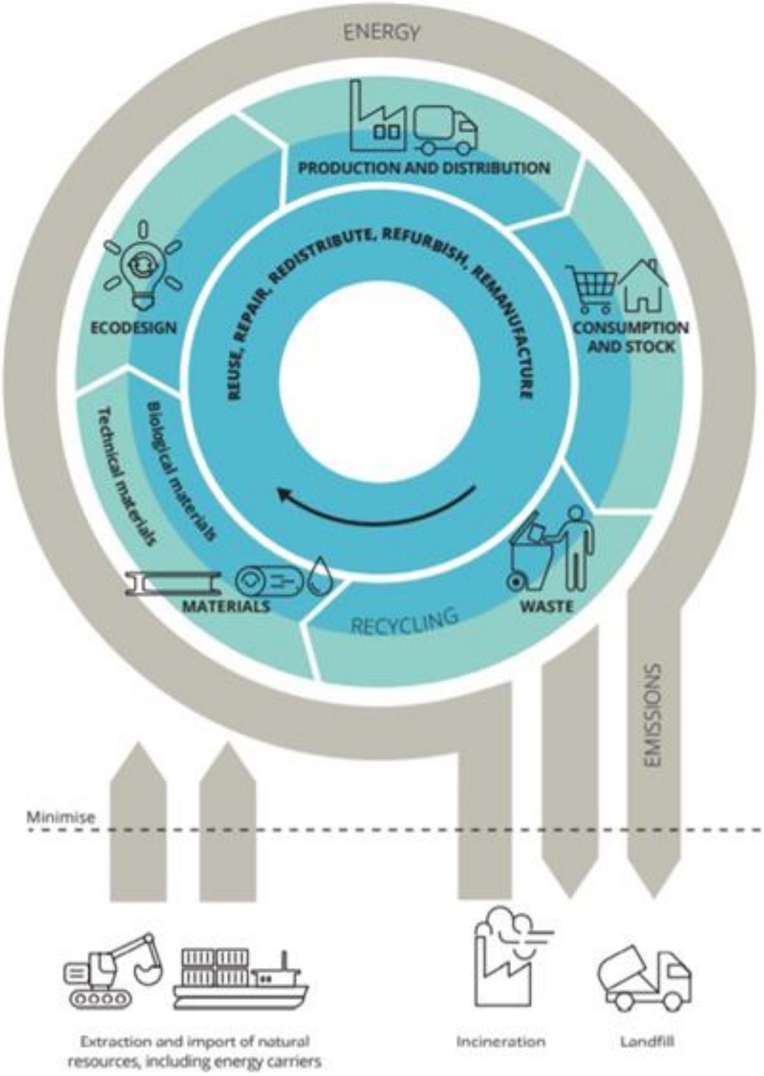
7.1 Impulses from new European Strategies

With its “Communication for a European Green Deal for the European Union and its Citizens”, the EC released a new growth strategy that aims “*to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use*” (EC, 2019).

Considered as an essential pathway for reaching climate neutrality by 2050 (EC, 2018), circular economy, already mentioned in this study, is a system-oriented approach defined as “*an economic system where the value of products, materials and resources is maintained in the economy for as long as possible*” (EC, 2015). The concept of circular economy is illustrated in Figure 7.1. Being one of the main blocks of the European Green Deal and building on actions implemented since 2015, the EC published a new Circular Economy Action Plan in March 2020. It presents a set of measures aiming to provide the adequate framework for accelerating the transition towards a more circular economy (EC, 2020a).

Characterised as a “*twin challenge*”, together with this new Circular Economy Action Plan, the EC concomitantly published A New Industrial Strategy for Europe (EC, 2020b). Being in the midst of two transformations which until now have rarely been aligned, the European Green Deal acknowledges and aims to address the interlinked challenges of the necessary ecological and digital transformations.

Figure 7.1: Circular economy system diagram



Source: EEA, 2019b

Having the potential to create 700 000 new jobs across the EU by 2030 (Cambridge Econometrics, Trinomics, and ICF, 2018), the transition towards a circular economy is now an essential component of this new EU Industrial Strategy and considered as one of the fundamentals underpinning Europe's industrial transformation.

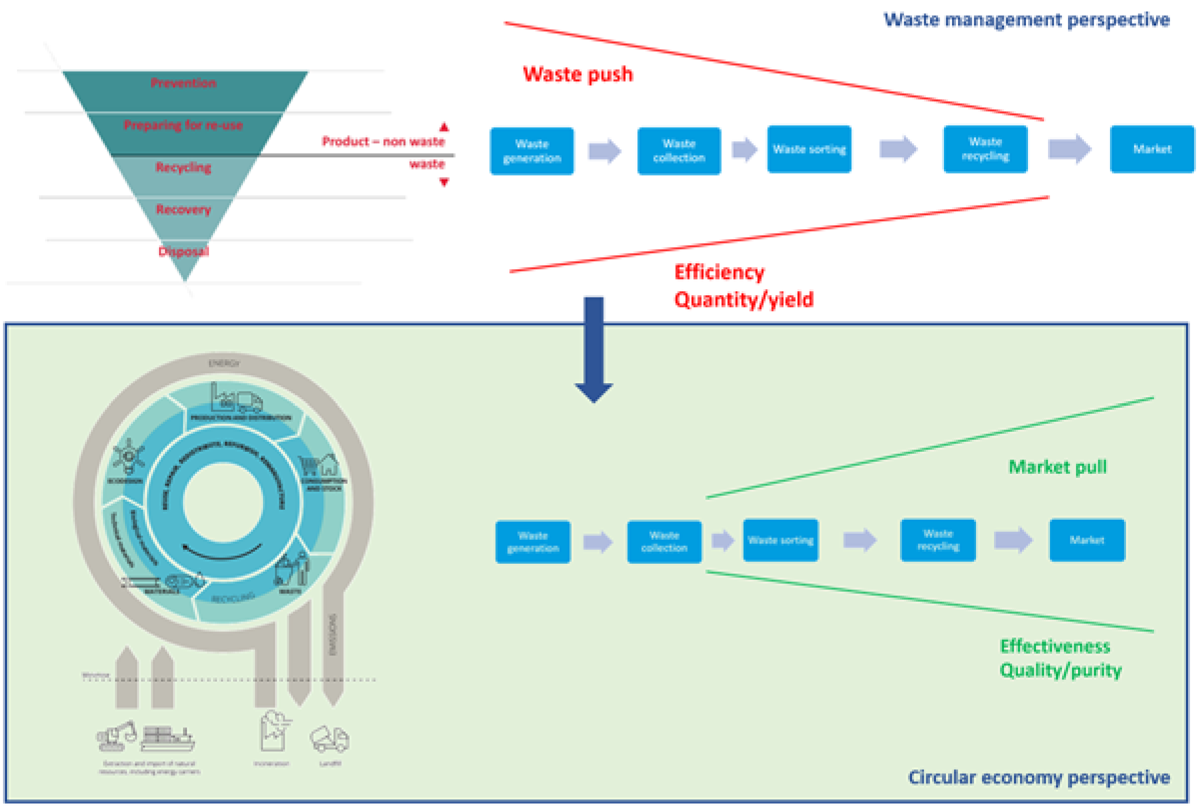
Illustrating those interrelated challenges, and thus reflecting this vision for a digitalised circular economy, both Communications on the European Green Deal and the EU Industrial Strategy consider digital technologies as a "critical enabler for attaining the sustainability goals of the Green deal in many different sectors".

In parallel, this industrial transformation is driven by the recent strategy on Shaping Europe's Digital Future in which the Commission defines a vision "f*or how Europe can retain its technological and digital sovereignty and be the global digital leader. Recognising that scalability is key in a digitalised economy, strengthening the digital single market will underpin Europe's transition*" and demands a "*European way to digital transformation which enhances our democratic values, respects our fundamental rights, and contributes to a sustainable, climate-neutral and resource-efficient economy*" (EC, 2020c).

Still according to the EU Industrial Strategy, by creating new business models, allowing industry to be more productive, providing workers with new skills and supporting the decarbonisation of our economy, digital technologies are "*changing the face of industry and the way we do business*" (EC, 2020b).

Being at the heart of measures listed in the new Circular Economy Action Plan, and coming back to the scope of this study, it is essential to understand the evolving role of waste management and prevention in this digitalised circular economy. Underlying elements of this role are shown in the diagram in Figure 7.2, increase of resource efficiency, prevention of waste generation and using waste as a resource, are important strategies towards such a circular economy. Since the 1970's major improvements in waste management occurred in Europe. The introduction of the waste hierarchy first shifted waste management from processing large volumes of waste towards the creation of value, bringing the focus to a need for more efficiency. The introduction of the circular economy concept by the EU, henceforth reinforced by the new Circular Economy Action Plan, provided the framework to shift from sustainable waste management - diverting waste from disposal over recovery to recycling (characterised as 'waste push') - to sustainable resource management, promoting the production of resources for which there is a high value secondary raw materials market (characterised as 'market pull'). Rather than finding a solution to manage large amounts of waste, the new approach asks how to produce secondary materials with the right quality for the materials market. This shift from a waste push to a market pull is conceptualised and illustrated in Figure 7.2. This conceptualisation also reflects that whereas current waste management targets relate to the weight of wastes, it is their quality that determines their value as secondary raw materials in the circular economy.

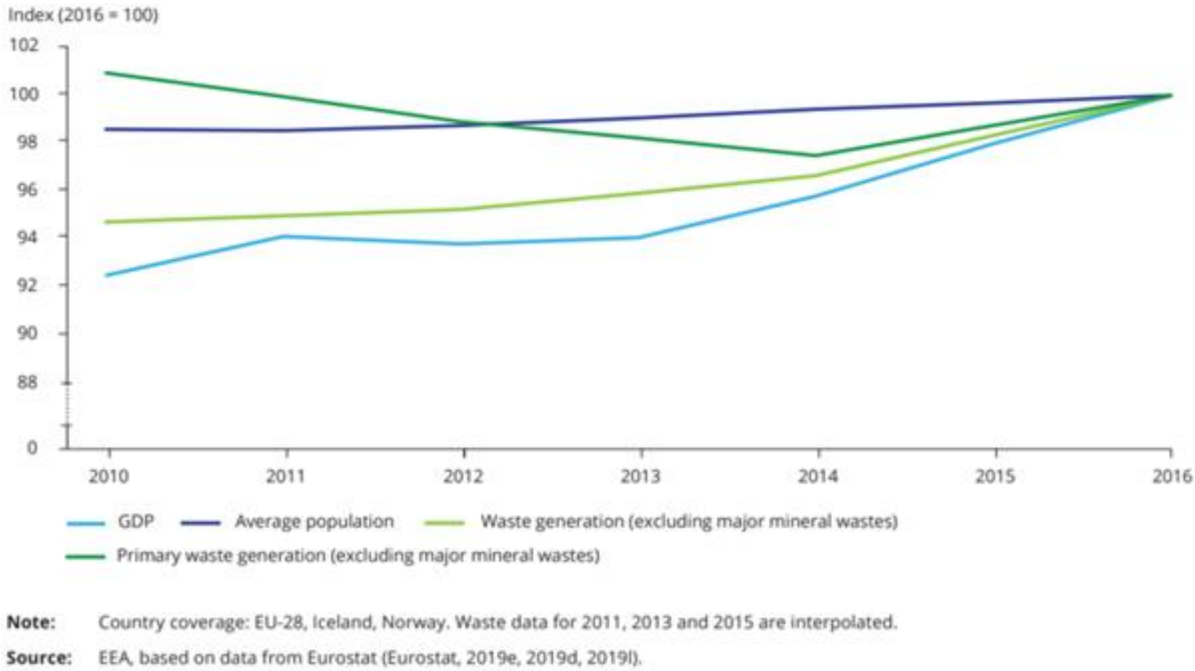
Figure 7.2: Circular economy concept shifts recycling from waste push to market pull.



Source: Own representation adapted from Vanderreydt et al. 2019.

The decoupling of waste generation from economic growth has not been successful yet and will require considerable efforts. As shown in Figure 7.3, the total amount of waste generated (excluding major mineral wastes) has increased in the 33 EEA member countries since 2010 alongside GDP (EEA, 2019). Still according to the EC, in order to enable this shift and decoupling, waste laws "*need to be modernised on an ongoing basis to make them fit for the circular economy and the digital age*", "*Rolling out the sustainable product policy and translating it into specific legislation will be key to making progress on waste prevention*" (EC, 2020a). Those policies and their implementation will have to enforce and enable waste prevention.

Figure 7.3: Trends in waste generation (excluding major mineral wastes), economic development and population, EEA-33.



As described before in this study, some digital technologies and their combination such as robotics, Internet of Things, Artificial Intelligence, Data Analytics and Distributed Ledger are deeply transforming our economies and have already demonstrated benefits, while sporadically, within the waste management sector (see chapter 4). It has also been shown that they are clear enablers for advancing the waste management regime (see chapter 5).

Bridging physical and virtual worlds, there is a clear consensus that a sound implementation of those digital technologies cannot only enable but also catalyse the necessary shift towards a circular economy as outlined above. A modernisation of waste laws on its own will not be enough, a shift towards less waste-intensive business models and extending product lifetimes will be essential. The next section will briefly introduce how and to which extent the use of specific digital technologies can facilitate a transition towards a more circular economy.

7.2 Using digital technologies to realise a circular economy

As mentioned above, increase of resource efficiency, prevention of waste generation and using waste as a resource are important strategies towards a more circular economy. It is important to understand that the above-defined circular economy system approach does not only aim at reducing the negative impacts of a linear economy by closing material loops through recycling. While recirculation of materials and a shift towards high quality recycling is indeed essential for building a circular economy, systemic changes along value chains are required, fundamentally changing patterns of production and consumption. Preventing waste generation and decreasing the demand for virgin material is usually considered as delivering higher environmental benefits than any other (circular) option. They reduce both the need to treat the resulting waste and the pressures from extracting virgin resources and producing the products in the first place.

The circular economy concept diagram shown in Figure 7.1, indeed reflects the importance of a holistic understanding taking into consideration all product lifecycle stages and value chain actors. Using a life cycle thinking approach throughout this section, it will be shown how digital technologies can contribute to the circular economy scheme. In addition to the advancement of the waste management regime, maintaining products and materials in the economy for as long as possible, subsequently preventing the generation of waste is a point in case here. Indeed, we and experts interviewed as part of the research for this project, expect that a full encompassing circular economy can only be achieved by the use of digital technologies. Past analyses have shown that especially information deficits along the product life cycle stages and between value chain actors of the circular economy have so far hindered the emergence of a circular economy. They cause uncertainties and burdens on quality, supply and transaction cost effectiveness as well as technological shortcomings. It is obvious that digital technologies are specifically suitable to solve these challenges (Wilts/Berg 2017).

7.2.1 Linking the physical and virtual worlds

As described in section 4.1.2, the IoT is connecting material and information flows and playing a central role for data collection. When combined with appropriate storage and analytics, collected data can be translated into relevant information for manufacturers to track, monitor, control, optimise or again provide some design evolution of their products.

7.2.1.1 Design

With regard to more advanced IoT capabilities, a feedback loop between a product's stages (use, end of life, design) can provide insights into effective product use and performance and subsequently inform design improvements (Ingemarsdotter et al., 2019). This feedback loop can facilitate the implementation of design thinking and human-centred design approaches necessary in a circular product design (Ellen Mac Arthur Foundation, n.d.a, Sitra, Technology Industries of Finland and Accenture, 2018). Taking advantage of product-in-use data for design improvements can lead to a reduction of a product's environmental impact, illustrating one potential benefit of the use of digital technologies at the design stage.

Still targeting this design stage, digital technologies can be used for dematerialisation, which could subsequently lead to preventing the generation of waste. A Czech start-up, MIWA, introduced a digital solution connecting different stakeholders along the food value chain. Through a mobile application, customers can order the exact quantities of groceries needed, which are then delivered in reusable packaging to either their nearest store or directly to their home. This solution does not only design out plastic packaging, it also helps to minimize food waste (Ellen Mac Arthur Foundation, n.d.b).

7.2.1.2 Manufacture & use

Increasing reliability of manufacturing processes and extending product lifetime are important circular strategies and sources of waste prevention. Minimising wear through predictive, preventive or reactive maintenance and repair, or through updates are additional, potentially digitally-enabled or supported beneficial activities in a circular economy. Manufacturers can monitor their operations with an automatic analysis of sensor data to help generate alarms when the production machine begins to deviate from the expected operation. This can make it possible, for instance, to avoid the production of low quality products that would be discarded otherwise (Kristoffersen et al., 2020).

At a product level and as described by Ingemarsdotter et al., "[digital] *tracking allows maintenance actors to identify and locate products that need to be serviced. Moreover, products can monitor their own use and status, and send alerts about when they need maintenance, and which spare parts to order. The capability of control can also enable remote maintenance, repair, and upgrades. In advanced cases, companies continuously monitor the condition of products and apply prediction models that allow them to optimally plan and execute maintenance before a product fails*" (Ingemarsdotter et al., 2019).

7.2.1.3 Reuse/Refurbish

The above-mentioned digitally-enabled capabilities can even further maximise the functionality and value of products by facilitating reuse or refurbishment activities. Monitoring the condition and/or controlling of a product, or specific parts, can facilitate the implementation of take-back systems but also assess the (remaining) performance. This "performance" information could be linked to new certification processes, certifying the suitability for specific second-hand markets.

Another example of a well-established and well-working digital solution for reuse are second hand marketplaces, such as gumTree or eBay, which also play an important role for waste prevention. The ability of digital platforms to decrease the effort for finding the right offer is exploited. Demand and supply are matched on a very individual level. It may be hypothesised that there is an additional effect through an incentive to buy long-lasting products that can be resold on these marketplaces. While for larger items, such as cars, these considerations are part of the criteria to purchase a certain brand or model, a similar trend has not been proven yet for household goods. If applicable, this would result in further decrease of waste and in economic pressure to produce long lasting goods.

7.2.2 Towards Product-Service Systems

As introduced above, an underlying element in a transition towards a circular economy is the collaboration within and across value chains and among their stakeholders. Improving traceability and transparency during product lifetimes is thus essential. Connecting those materials and information flows in a so-called "digital product passport" and securely communicating that information to selected stakeholders in the value chain thanks to distributed-ledger technology is a potential additional use of digital technologies in a circular economy (Wilts and Berg, 2017). The Dutch start-up, Circularise, is for instance developing a blockchain-based communication protocol called "smart questioning" to promote value chain transparency without public disclosure of datasets or supply chain partners.

Having the mission to move the building industry towards a circular economy, the H2020 project Buildings As Material Banks (BAMB) developed more than 300 electronic materials passports together with a software solution. BAMB material passports are sets of data describing defined characteristics of materials in products that give them value for recovery and reuse (BAMB, 2020).

Using a life cycle thinking approach allows for understanding how the use of digital technologies can contribute to maintaining products and materials value in the economy. It has also demonstrated the even greater potential that can be achieved by those digitally-enabled capabilities. Generating information for tracking, monitoring, controlling, optimising and redesigning products also allows to rethink how value is generated and maximised. This transition towards a data-driven culture might concomitantly lead to more service-oriented business models such as product service systems, especially in a business-to-consumers context (already more mature in a business-to-business context) (EEA, 2017). This shift towards service-oriented business models is indeed considered as a powerful way of maximising product value, if product ownership remains with the producer. In that case, minimising the total lifecycle cost of the product is an economic incentive that can for instance encourage the design of products for longer lifespans, repair, reuse or refurbishment. Examples for product service systems are digitally enabled sharing models, which lessen the need for personal belongings and have the potential to limit resource use, and consequently waste generation.

8 Conclusion

The report has shown that the waste management sector is in a transition phase towards the diffusion of digitalisation. At present, individual digital technologies are able to address every instance in the waste management system from operational and logistic tasks like collection and sorting to communication. By and large, the main focus in each instance is set on improvement in efficiency by automation or support, but also improvement of service is an important aspect. However, up to now there is no fully integrated digital system that covers the full waste management sector. Emerging technologies and their integration are likely to close this gap. Moreover, highly automated or even autonomous systems are expected to emerge, but fully autonomous vehicles for collection may still be ten to twenty years away.

There are hints for many technologies to also alleviate the environmental impact of generated waste and the waste management sector itself. However, in several cases, holistic impact assessments are necessary for validating those savings and limiting any potential rebound effects for individual deployment. Furthermore, digital technologies can contribute to improvements in health and safety.

The analysis has also shown that the degree of digitalisation differs considerably not only between, but also within countries and between private and public entities. Certain drivers for the application of digital technologies now and in the future were identified, among them economic drivers like cost pressure, environmental drivers such as climate protection and the growing importance of the circular economy, and drivers from other sectors like urbanisation. Inhibitors often refer to knowledge gaps concerning the use and application of digital technologies as well as their chances and opportunities. Moreover, the lack of a suitable digital infrastructure such as mobile communication networks poses a problem. Investment costs and resistance from employees are among further barriers that were identified.

It was shown that digital technologies provide ample opportunities for the waste management sector, waste prevention and the circular economy. In the EU, digital transformation is seen as a huge trend transforming many different sectors and will be addressed as one of the top priorities in the coming years. Digitalisation and automation allow to streamline processes, enabling the waste management sector to handle increasing amounts of waste and materials, and support its changing role moving from waste handling to material management in a circular economy. Currently, important digital technologies in the field of waste management are robotics, the internet of things, cloud computing, data analytics and artificial intelligence.

Through digital technologies, tasks that are hazardous for humans can be automated, the efficiency of processing can increase, higher purity of waste streams can be reached by improved sorting, and the fraction of waste that is recycled instead of incinerated or landfilled can be increased. Moreover, communication with citizens and customers can be improved and streamlined. At present, digital technologies in waste management are mainly applied in the sectors communication and waste collection and for internal processes. The technology survey shows that many further challenges in the waste sector can be addressed with digital tools.

Even though some waste data is collected and made available by public actors, there’s still a major knowledge gap that needs to be closed through research. Digital recycling technologies and waste prevention need further research to be improved in order to lower the environmental impact of our society, specifically with a focus on waste prevention and the whole circle. A horizon scanning analysis should be carried out in order to detect and recognise digital technologies more explicitly that can help achieve the goals that have been set for sustainable waste management.

Various other sectors have seen radical changes induced by the new digital possibilities, with completely new business models. Those changes have eliminated established players that had been dominating their sector over decades. Similar transformations could take place in the waste sector even though changes will be less radical since the core aspect, waste, cannot be virtualised and municipal actors cannot be forced out of business.

The evolution of the waste management sector and the necessary shift (from waste push to market pull, see chapter 7) towards a circular economy, can profit immensely from the use of digital technologies. The digital integration of recycling streams to create more circular supply chains is one point in case here. Implications in this area need to take into account that the waste management sector and also the circular economy have to fulfil a number of obligations that transcend economic success and viability and specifically relate to concerns of health, hygiene, safety and environmental protection.

Overall, the matter of the digital transformation of waste management and prevention in a circular economy is under-researched and requires much more analysis. Several topics are relevant here:

- The heterogeneity within Europe with regard to the digitalisation of the waste management sector needs to be understood and managed. Digitally leveraging waste management across Europe through digital technologies could significantly strengthen the emergence of the circular economy.
- The concrete impact of digital technologies in this area with regard to resource and energy efficiency as well as other environmental impacts needs to be understood and validated holistically and more deeply. Specifically, the risk of rebound effects in the economic, social and environmental areas needs to be analysed and hedged accordingly.
- The effects of digitalisation explored in chapter 6 require a deep and systematic understanding, especially interdependencies between the different dimensions should be considered.
- Regular technology scouting and horizon scanning for this field should be conducted and should involve both the circular economy as a whole and the waste management sector.
- The role and functions of the waste management sector in a full-fledged digital circular economy needs exploration and analysis, as it may change considerably. For example, the need for compatibility of interfaces should be addressed, but also the role of public waste management agents in such a system needs investigation.

With the move from waste handling, to a recycling society and ultimately to a resource efficient circular economy, the role of the policy maker will also change from a controlling function in waste management to an enabling factor in material management and product policy. Policy actions need to focus on waste prevention and on responsibility of producers, and this requires a stimulating approach through communication campaigns for consumers and the promotion of responsibility amongst manufacturers and industry players. The role of the authority therefore has shifted from command and control to include much more stakeholder motivation and involvement.

Digitalisation should be seen as a tool to enable these changes. An example could be enforcement of product and environmental data collection. This data stock can then be used to understand more about the functionality, gaps and chances of the waste business. Harmonisation of reporting methods would allow for easier comparison and goal setting in the waste sector. An important aspect as well will be the definition of interfaces between different digital solutions to prevent monopolies and platform businesses where they are disadvantageous to innovation, progress and economic welfare. Publicly available interfaces, that make transition from one commercial provider to another possible, help to lower this risk. The Austrian government, for example, chose to define such standards. And while the role of politics to set these standards can be debated, policy could at least enable and supervise this process to ensure that all concerned parties are well represented in defining them.

In general, the field of waste treatment seems to be too heterogeneous with regard to digitalisation to point out one single strategy. The report shows that there is a spread in digital adoption between private and public waste businesses, with the private ones being faster in adopting digital technologies. Investments into digital technologies especially for public waste management may go with investment cycles and the priorities that are given (or not) to waste management by local authorities. Moreover, investment costs may be prohibitive for these actors, especially as long as there is no pressure from competitors or regulation. The introduction of new collection bins, trucks, and so on., will then be combined with the introduction of sensors, trackers, etc. More investigation into the level of investment and endowment of digital technologies in European waste management is needed. This may currently be important, as a window of opportunity for investment is there and especially countries and municipalities, who are lagging in waste management and circular economy, may use digital technologies for leapfrogging into a more sustainable regime.

For public actors in waste treatment, the fact that they do not compete with each other can allow for the joint development of digital solutions. If software is developed specifically for one public player, it should be made sure that the underlying code is made publicly available so that other actors can use and improve it, as is the case for many open source projects. Private companies should use digital technologies to improve recycling and resource use. The (financial) incentives for this will most likely be set by legislation to achieve the environmental goals set. If our society shifts from disposing waste to using it as a resource, both private and public waste companies will have to redefine their role transitioning from a disposal company to a raw material supplier.

Implications for a policy towards digitalising the waste management sector are inter alia:

- Digital technologies can be a huge empowerment for the emergence and creation of a circular economy, while circular economy may alleviate some challenges put forth by digitalisation. Political strategies in both directions should hence make use of this mutuality. Digital development of the waste management sector should thus be endorsed in coordination with the development of a circular economy as supported by the Circular Economy Action Plan and the Industrial Strategy. This implies two requirements:
    - Firstly, sorting and recycling undertaken in the waste management sector are vital ingredients towards a circular economy and hence should be treated as an integral part of a digital industrial transformation on the systems level.
    - Secondly, on the technological level, this requires suitable interfaces as well as obligatory, standardised and integrated data flows between sectors and relevant stakeholders of a circular economy. Ensuring compatibility between different systems can be important here for several reasons. Inter alia, it maintains competition on the markets and for technological development, it prevents the dangers of monopolies, and may make investments more future proof given that compatibility is maintained over time.

- Digital technologies for various applications in the waste management sector are developed and produced in Europe. As waste management is an ubiquitous concern, strengthening technology development in this regard may prove to be a chance for European companies and the European economy.
- Digital applications in waste management require a working infrastructure, for example, in terms of well-established communication systems of various sorts. While this is not a specific requirement of digital technologies in waste management only, this specific sector needs to operate in every inhabited area of Europe to fulfil its important obligations for health, safety and environment. Cross-border operable infrastructure might be of special interest in some regions.
- Digitalisation in the area of waste management and prevention should be managed in an approach that is oriented towards existing problems and opportunities. It is important that digitalisation is not enforced for its own sake.
- Since waste management is an effort that involves many administrative levels (for example, in Germany the Federal Government, federal states ("Bundeslaender") and municipalities are part of the waste management administration, working together with several forms of private and public waste management agents and subject to European laws, directives and regulations), efforts for an integrated, digitalised waste management regime should be orchestrated as coordinated efforts considering the needs and requirements of the individual players.

9 Key messages

This chapter provides an overview of the report's key messages.

1. *Digital technologies can become a crucial asset to shift the European waste management sector towards a sustainable materials management role.* They can improve waste collection and treatment for example through resource and route planning, data analytics, and communication with citizens, consumers and customers. They can improve recycling on the side of producers through facilitating use of recyclates, on the side of consumers through enabling better purchasing and sorting decisions, and on the recyclers' side by improved waste sourcing. This evolution is in line with the changing focus from waste treatment to materials management.

2. *Digitalisation in waste management and treatment, specifically for public bodies, is mostly in an innovation phase with some technologies diffusing more broadly.* The current situation seems very heterogeneous in Europe but also within the European nations. Technologies for all steps in the process exist and all major digital technologies (AI, DLT, Robotics, etc.) are being applied but not as consistent and integrated systems. New business models as waste trading platforms, waste specific software suits and business analytics are emerging. The application of digital technologies changes the cost structure from operations driven to capital driven.

3. *There are both drivers and inhibitors of digitalisation in the waste management sector.* Drivers are cost pressure, business models, customer expectations, pull towards Circular Economy, climate crisis, extended producer responsibility, waste amounts, urbanisation. Inhibitors are lack of digital literacy, investment costs, security concerns, fear of job loss, missing digital ecosystem.

4. *Rebound effects in the economic, social and environmental dimension require constant attention and adjustment.* Digitalisation will enhance productivity and lead to a shift from unskilled to skilled work. Ensuing effects on the labour market, also the informal one, need to be clarified.

5. *The digital transformation of the waste management sector should be aligned and combined with the plans for and the digitalization of a full-fledged circular economy* to ensure synergies and prevent frictions. The European strategies acknowledge the interconnected challenges and beneficial synergies between the green and digital transformations, and emphasise the key role of EU industry for unlocking their potential.

6. *Infrastructure such as radio networks and ubiquitous internet access are pivotal for a successful digital transformation of the waste sector.* Many digital solutions rely heavily on connectivity, network infrastructure, standards and interfaces. These are needed to enable data transmission and interoperability of different systems and applications. Lack thereof or insufficient infrastructure hence results in malfunctions, sunk costs and money loss due to inefficiency. Operations close to borders are of special interest here, since communication infrastructure can overlap, which may also result in dysfunctionalities.

7. *The area is under-researched and many questions are open.* Data on a European level is scarce or missing. Important questions such as future system architecture of a (European) digital waste management sector and its integration into a broader circular economy as well as into concepts such as smart cities are unsolved.

Literature

AMCS Group, 2020. amcsGroup.com . https://www.amcsgroup.com/ (accessed 12.02.20).

Andrae, A., 2020. *Hypotheses for Primary Energy Use, Electricity Use and CO2 Emissions of Global Computing and Its Shares of the Total Between 2020 and 2030*. WSEAS Trans. POWER Syst. 15. https://doi.org/10.37394/232016.2020.15.6

Andrae, A., Edler, T., 2015. *On Global Electricity Usage of Communication Technology: Trends to 2030*. Challenges 6, 117–157. https://doi.org/10.3390/challe6010117

Apple, 2020. Apple.com . *Apple erweitert weltweite Recyclingprogramme*. https://www.apple.com/de/newsroom/2019/04/apple-expands-global-recycling-programs/ (accessed 12.02.20).

Autowise.ai, 2020. autowise.ai . http://autowise.ai/ (accessed 12.02.20).

Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., International Telecommunication Union, United Nations University, International Solid Waste Association, 2017. *The Global E-waste Monitor 2017: quantities, flows, and resources.*

BAMB, 2020. *Materials Passports* [WWW Document]. Build. Mater. Banks - Mater. Passpt. URL https://www.bamb2020.eu/topics/materials-passports/ (accessed 5.20.20).

BBVA Research, 2016. *European urbanisation trends*.

BDE - Bundesverband der deutschen Entsorgungs-, Wasser- und Rohstoffwirtschaft and VKU - Verband Kommunaler Unternehmen, 2015. *mobile-IT*.

BDE - Bundesverband der deutschen Entsorgungs-, Wasser- und Rohstoffwirtschaft and VKU - Verband Kommunaler Unternehmen, 2016. *Mobile IT-Systeme - Technische Übersicht und Standards 2016*.

Berg, Wagner, Müller, Hänseler, Kuhn, forthcoming. *Innovationspotentiale der kommunalen Kreislaufwirtschaft durch Digitalisierung in Sachsen*.

BHS, 2020. max-ai.com . https://www.max-ai.com/ (accessed 12.02.20).

Bigbelly Inc, 2020. bigbelly.com . https://bigbelly.com (accessed 12.02.20).

BIR, 2020. wasteiq.no . https://www.wasteiq.no/ (accessed 12.02.20).

BSI - Bundesamt für Sicherheit in der Informationstechnik, n.d. *Digitale Gesellschaft. Cloud Computing Grundlagen*.

Burgard, 2018. *Künstliche Intelligenz., Expertise für das WBGU-Hauptgutachten „Unsere gemeinsame digitale Zukunft“*. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen.

Cambridge Econometrics, Trinomics, and ICF, 2018. *Impacts of circular economy policies on the labour market.* European Commission.

c-trace GmbH, 2020. c-trade.de . https://www.c-trace.de/de-DE/home/ (accessed 12.02.20).

CiA - CAN in Automation, 2019. CleANopen . https://www.can-cia.org/news/cia-in-action/view/cleanopen-updated/2019/1/8/ (accessed 13.02.20).

CNIM Group, 2020. cnim.com . https://cnim.com/en/businesses/treatment-and-recovery-waste#services-waste-to-energy-conversion-plants (accessed 12.02.20).

Deutscher Bundestag, 2017. 1. Untersuchungsausschuss ('NSA') . https://www.bundestag.de/ausschuesse/ausschuesse18/ua/1untersuchungsausschuss (accessed 17.02.20).

Digital Europe Programme, 2019. A proposed €9.2 Billion of funding for 2021-2027 . Shap. Eur. Digit. Future - Eur. Comm. https://ec.europa.eu/digital-single-market/en/news/digital-europe-programme-proposed-eu92-billion-funding-2021-2027 (accessed 19.02.20).

Directive, E. C. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union L*, *312*(3). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098 (accessed 24.06.20).

Eco Mobile, 2020. ecomobile.hr . https://www.ecomobile.hr (accessed 12.02.20).

Ecobins, 2020. ecobins.pl . http://ecobins.pl/de/ (accessed 12.02.20).

ECOnX Waste Solutions B. V., 2020. econx.eu . http://econx.eu (accessed 12.02.20).

Ellen Mac Arthur Foundation, n.d.a. *Circular Design.* https://www.ellenmacarthurfoundation.org/explore/circular-design (accessed 22.06.20).

Ellen Mac Arthur Foundation, n.d.b. *MIWA - Czech Republic - Delivering groceries without single-use packaging and cutting household plastic waste. https://www.newplasticseconomy.org/innovation-prize/winners/miwa*

Empto, n.d. empto | Ihr digitaler Abfallassistent . *Empto Digit. Waste Assist*.

https://empto.de (accessed 21.02.20).

EMZ, 2020. emz environmental technology.

https://www.emz-et.com/en/home/ (accessed 5.20.20).

ENWAY, 2020. *Autonome Kehrmaschinen für industrielle Umfelder* .

https://enway.ai/de (accessed 20.02.20).

EPC - European Policy Centre, 2019. *Creating a digital roadmap for a circular economy*.

European Commission, 2015. *Closing the loop - An EU action plan for the Circular Economy.*

European Commission, 2018. *A Clean Planet for All - A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy.*

European Commission, 2019. *The European Green Deal.*

https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640

European Commission, 2020a. *A new Circular Economy Action Plan - For a cleaner and more competitive Europe.* https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Commission, 2020b. *A new Industrial Strategy for a globally competitive, green and digital Europe.*

European Commission, 2020c. *Shaping Europe´s digital future.*

https://ec.europa.eu/info/sites/info/files/communication-shaping-europes-digital-future-feb2020_en_4.pdf

European Comission, n.d. *Advanced technologies | Internal Market, Industry, Entrepreneurship and SMEs* https://ec.europa.eu/growth/industry/policy/digital-transformation_en (accessed 19.02.20).

European Environment Agency, 2017. *Circular by design - Products in the circular economy.*

European Environment Agency, 2019a. *Preventing plastic waste in Europe* — European Environment Agency.

European Environment Agency, 2019b. *The European Environment - State and Outlook 2020*.

European Parliament, 2015. *Briefing - Understanding waste management: policy challenges and opportunities.*

EWAS project, n.d. *Efficient and sustainable waste management methodologies using ICT tools enabling GHG emissions reduction* . http://life-ewas.eu/en/ (accessed 20.02.20).

Finanzen100, 2020. Top100: *Die wertvollsten Firmen an der Börse* .

https://www.finanzen100.de/top100/die-grossten-borsennotierten-unternehmen-der-welt/ (accessed 14.02.20).

GeSI - Global e-Sustainability Initiative, 2015. *#SMARTer2030 - ICT Solutions for 21st Century Challenges*.

Going Digital (GD) Horizontal Project, 2017. *Making the transformation work for growth and well-being.*

Hedberg, Sipka, 2020. *The circular economy. Going digital*.

IEA - International Energy Agency, 2017. *Digitalisation & Energy.*

IFR - International Federation of Robotics, 2017. *The Impact of Robots on Productivity, Employment and Jobs.*

IFR - International Federation of Robotics, 2019. *IFR Press Conference Presentation*.

IK Industrievereinigung Kunststoffverpackungen e.V., 2020. *Eco Design of Plastic Packaging*

https://ecodesign-packaging.org/en/

Industrial embedded systems, n.d. CleANopen .

http://industrial.embedded-computing.com/news/cleanopen-updated/ (accessed 13.02.20).

Infopulse, n.d. *Waste Management Chatbot for Environmental Organisation* .

https://www.infopulse.com/case-studies/waste-management-chatbot-for-environmental-organisation/ (accessed 21.02.20).

Ingemarsdotter, E., Jamsin, E., Kortuem, G., Balkenende, R., 2019. *Circular Strategies Enabled by the Internet of Things—A Framework and Analysis of Current Practice*. Sustainability.

insecarm.org, 2020. *Watch live surveillance online - IP cameras by rating*.

http://insecam.org/en/byrating/ (accessed 17.02.20).

ISWA – International Solid Waste Association, 2011. *ISWA Key Issue Paper on Waste Prevention, Waste Minimisation and Resource Management.*

ISWA – International Solid Waste Association, 2017. *The Impact of the 4th Industrial Revolution on the Waste Management Sector.*

ISWA – International Solid Waste Association, 2019. *How Industry 4.0 transforms the waste sector.*

ISB Global Ltd., 2020. *Cloud Computing Services* .

https://www.isb-global.com/cloud-computing/cloud-computing-services/ (accessed 12.02.20).

Katz, R., 2017. *Social and economic impact of digital transformation on the economy.* ITU

Kinnaman, T.C., 2009. *The economics of municipal solid waste management*. Waste Manag. 29, 2615–2617. https://doi.org/10.1016/j.wasman.2009.06.031

Kristoffersen, E., Li, Z., Li, J., Jensen, T. H., Pigosso, D. C. A., & McAloone, T. C., 2020. *Smart Circular Economy: CIRCit Workbook 4*. Technical University of Denmark.

Mainzer, 2016. Künstliche Intelligenz – Wann übernehmen die Maschinen.

Janson, M., 2019. *2020 überholt die Cloud lokale Speichermedien*. Statista Infografiken.

https://de.statista.com/infografik/18231/cloud-vs-lokaler-speicher/ (accessed 14.02.20).

Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., 2011 . *Addressing the Rebound Effect, a report for the European Commission DG Environment*.

Messenger, 2018. Wearable Robotics Boost Efficiency at Japanese Recycling Facility .

https://waste-management-world.com/a/wearable-robotics-boost-efficiency-at-japanese-recycling-facility (accessed 5.20.20).

MOBA - Mobile Automation, 2020. moba-automation.de .

https://moba-automation.de/maerkte-und-loesungen/abfallwirtschaft/software/mawis-web/ (accessed 12.02.20).

Nakamoto, 2008. *Bitcoin: A Peer-to-Peer Electronic Cash System*.

Negreiro, Tambiama - European Parliamentary Research Service, 2019. *Digital transformation*.

Nicolas, Berg, 2019. *Overview of existing blockchain networks worldwide regarding recovery and*

recycling of plastics – Business Ideas & Models, Revenues and Blockchain Provider.

NIST (National Institute of Standards and Technology), 2011. *The NIST Definition of Cloud Computing.*

Recommendations of the National Institute of Standards and Technology.

Nordsense, 2020. nordsense.com. https://nordsense.com (accessed 12.02.20).

OECD – Organisation for Economic Cooperation and Development, 2017a. OECD Science, Technology and

Industry Scoreboard 2017 - Graph 1.30 Dispersion of sectors in each considered dimension of digitalisation, 2013-15.

OECD – Organisation for Economic Cooperation and Development, 2017b. *Key issues for digital*

transformation in the G20.

OECD – Organisation for Economic Cooperation and Development, 2017c. *OECD Employment Outlook 2017, OECD Publishing, Paris, https://doi.org/10.1787/empl_outlook-2017-graph39-en.*

OECD – Organisation for Economic Cooperation and Development, 2019a. *The Future of Work.*

OECD Employment Outlook 2019.

OECD – Organisation for Economic Cooperation and Development, 2019b. *Measuring the Digital Transformation: A Roadmap for the Future*, OECD Publishing, Paris, https://doi.org/10.1787/b045289f-en.

Oneplus Systems Inc., 2020. oneplussystems.com. https://oneplussystems.com (accessed 12.02.20).

Open Resource, 2017. *Waste management enters the digital revolution* .

https://openresource.suez.com/en/-/waste-management-enters-the-digital-revolution

(accessed 24.06.20)

Paul Mozur - New York Times, 2018. *Inside China's Dystopian Dreams: A.I., Shame and Lots of Cameras*.

https://www.nytimes.com/2018/07/08/business/china-surveillance-technology.html

(accessed 14.02.20).

Phung, C. G., 2019. *Implications of the circular economy and digital transition on skills and green jobs in the plastics industry.* Field Actions Science Reports. http://journals.openedition.org/ factsreports/5498

Refind Industries, 2020. refind.se. https://www.refind.se (accessed 12.02.20).

Resource International, 2020. resourceintl.com . https://www.resourceintl.com/ (accessed 12.02.20).

RFI, 2018. *Max - the robot recycler who outperforms humans* . RFI.

http://www.rfi.fr/en/environment/20181011-max-robot-recycle-waste-disposal-environment-artificial-intelligence-human-job- (accessed 25.02.20).

Robot Institute of America, 1979. Definition of Robot.

Rubicon Global Holdings LLC., 2020. rubiconglobal.com

https://www.rubiconglobal.com/rubicon-select/ (accessed 12.02.20).

Samsara Networks Inc., 2020. samsara.com . https://www.samsara.com/de/fleet/routing

(accessed 12.02.20).

Sitra, Technology Industries of Finland and Accenture, 2018. *Circular economy business models for the manufacturing industry - Circular Economy Playbook for Finnish SMEs.*

Smart Recycling, 2020. smart-recycling.se . https://www.smart-recycling.se (accessed 12.02.20).

SmartBin, 2020. smartbin.com . https://www.smartbin.com/solutions/iot-level-sensors/

(accessed 12.02.20).

SSI Schäfer, 2020. iob.ssi-schaefer.com . https://iob.ssi-schaefer.com (accessed 12.02.20).

StalkIT AS, 2020. stalkit.no . https://stalkit.no (accessed 12.02.20).

Symantec Security Response, 2016. *IoT devices being increasingly used for DDoS attacks* .

http://www.symantec.com/connect/blogs/iot-devices-being-increasingly-used-ddos-attacks (accessed 17.02.20).

teXXmo Mobile Solution GmbH, 2020. iot-button.eu . http://iot-button.eu (accessed 12.02.20).

TheCircularLab, 2018. *A.I.R-e is born, the first virtual recycling assistant created by TheCircularLab.*

https://www.thecircularlab.com/en/a-i-r-e-is-born-the-first-virtual-recycling-assistant-created-by-thecircularlab/ (accessed 24.06.20)

TouchStar Technologies Ltd., (UK), 2020. touchsstar.co.uk [WWW Document]. URL

https://www.touchstar.co.uk/products-services/electronic-proof-delivery

(accessed 2.12.20).

University Bamberg, 2019. Press Release - *Retouren: Warum 20 Millionen Artikel vernichtet werden*.

van Leeuwen, T., Siebenlist, M., Alnajar, S., Hardjopawiro, J., 2020. *Collectors - Work package 3: Quantification of costs and benefits - Assessment of socio economic and financial performance of 12 selected case studies*.

Vanderreydt, Nelen, Rosa, Debree, 2019. Task 2.1 - *Identification of main boundary conditions for better-performing waste collection systems*.

Verein Deutscher Ingenieure e.V., 1990. VDI 2860:1990-05 (withdrawn).

Volvo Group, 2020. volvogroup.com .

https://www.volvogroup.com/en-en/news/2017/may/news-2561936.html (accessed 12.02.20).

Waste Logics Software Ltd., 2020. wastelogistics.com . https://www.wastelogics.com

(accessed 12.02.20).

Wilts, C.H., Berg, H., 2017. *Digitale Kreislaufwirtschaft : die digitale Transformation als Wegbereiter ressourcenschonender Stoffkreisläufe (Wuppertal InBrief)*. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal.

Zen Robotics, 2020. zenrobotics.com . https://zenrobotics.com/reference/remeo/ (accessed 12.02.20).

Abbreviations

AI	artificial intelligence
IR	infrared
EU	European Union
EC	European Commission
OECD	Organisation for Economic Co-operation and Development
US	United States
AT	Austria
DK	Denmark
FI	Finland
FR	France
UK	United Kingdom
IT	Italy
NL	Netherlands
SE	Sweden
EEA	European Environment Agency
CPU	core processing unit
GB	gigabyte
USD	United States dollar
IoT	internet of things
VDI	Verein deutscher Ingenieure – association of german engineers
IFR	International Federation of Robotics
kg	kilogramm – 1000 gramm
RFID	radio frequency identification
NFC	near field communication
ISWA	International Solid Waste Association
QR	quick response
GDPR	General Data Protection Regulation
GIS	geographic information system
NIR	Near-infrared
GPS	global positioning system
ICT	information and communication technology
ERP	enterprise resource planning
ID	identification
LCA	life cycle analysis

WEEE	waste electrical and electronic equipment
GeSI	Global e-Sustainability Initiative
EPR	extended producer responsibility
IT	information technology
TV	television
IaaS	Infrastructure as a Service
PaaS	Platform as a Service
SaaS	Software as a Service
DLT	distributed ledger technology
IEA	International Energy Agency
OPEX	operational expenditure
CAPEX	capital expenditure
GDP	gross domestic product

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