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Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review

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ABSTRACT

The general aim of circular economy is the most efficient and comprehensive use of resources. In order to achieve this goal, new approaches of Industry 4.0 are being developed and implemented in the field of waste management. The innovative K-project: *Recycling and Recovery of Waste 4.0 - "ReWaste4.0"* deals with topics such as digitalisation and the use of robotic technologies in waste management. Here, a summary of the already published results in these areas, which were divided into the four focused topics, is given: Collection and Logistics, Machines and waste treatment plants, Business models and Data Tools. Presented are systems and methods already used in waste management, as well as technologies that have already been successfully applied in other industrial sectors and will also be relevant in the waste management sector for the future. The focus is set on systems that could be used in waste treatment plants or machines in the future in order to make treatment of waste more efficient. In particular, systems which carry out the sorting of (mixed) waste via robotic technologies are of interest. Furthermore "smart bins" with sensors for material detection or level measurement, methods for digital image analysis and new business models have already been developed. The technologies are often based on large amounts of data that can contribute to increase the efficiency within plants. In addition, the results of an online market survey of companies from the waste management industry on the subject of waste management 4.0 or "digital readiness" are summarized.

Contents

Abbreviations: BIM, Building Information Modelling; BM, Business Models; CL, Collection and Logistic; CNN, Convolutional Neural Networks; DACH-region, "Germany-Austria-Switzerland-Region"; DT, Data Tools; EMS, Electromagnetic Sensor; EPC, Engineering, Procurement and Construction; GI, General Information; HMI, Human Machine Interface; ICT, Information- and Communication-technology; IoT, Internet of Things; LIBS, Laser Induced Breakdown Spectroscopy; MIR, Mid-infrared; MP, Machine and Plants; M2M, Machine-to-Machine; NFC, Near Field Communication; NIR, Near-Infrared; PCNN, Pertained Convolutional Neural Networks; PMPG HW, Paper, Metal, Plastic and Glass household waste; RFID, Radio-Frequency Identification; SWFN4.0, Smart Waste Factory Network; VIS, Visible; XRF, X-Ray-Fluorescence; XRT, X-Ray-Transmission.

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1. Introduction

As part of the project: *Recycling and Recovery of Waste 4.0 - "ReWaste4.0*" at the Chair of Waste Processing Technology and Waste Management of the Montanuniversitaet Leoben, new process, plant and machine concepts for new and existing secondary raw material markets are being developed on a scientific and technical level. For the first time, new "Industry 4.0" approaches (e.g. "digital networking", "robotics", etc.) will be elaborated for the waste management sector to further develop waste management towards circular economy. Special focus lies on the examination and implementation of digitally connected recycling- and recovery processes with the highest quality (Sarc and Pomberger, 2018).

1.1. Status and development of municipal waste management in the EU

Relevant for this contribution is mainly waste that can be assigned to the waste main group "municipal waste", which has been defined by the European Union in Directive 2018/851 amending Directive 2008/98/EC on waste in Article 3 (2) as follows (European Union, 2018b):

> *"Municipal Waste means:*
> *(a) mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture;*
> *(b) mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households;*
> *Municipal waste does not include waste from production, agriculture, forestry, fishing, septic tanks and sewage network and treatment, including sewage sludge, end-of-life vehicles or construction and demolition waste."*

The European Circular Economy Package redefines the required recycling rates and the maximum landfill rate for municipal waste. Article 11 (2) of the amendment to Directive 2008/98/EC on waste (European Union, 2018b) states the following:

> *"In order to comply with the objectives of this Directive, and move to a European circular economy with a high level of resource efficiency, Member States shall take the necessary measures designed to achieve the following targets:*
> *...(c) by 2025, the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 55% by weight;*
> *(d) by 2030, the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 60% by weight;*
> *(e) by 2035, the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 65% by weight."*

Article 5 (5) of the amendment to Directive 1999/31/EC on the landfill of waste (European Union, 2018a) states:

> *"Member States shall take the necessary measures to ensure that by 2035 the amount of municipal waste landfilled is reduced to 10% or less of the total amount of municipal waste generated (by weight)."*

In order to meet the demands of the target rates set by the EU, the member states are required to optimize the national waste management in the direction of circular economy.

To verify compliance with the municipal waste targets set out in the guidelines, the following points, as set out in Article 11a (1), become valid following the amendment of Directive 2008/98/EC on waste (European Union, 2018b):

> *"For the purpose of calculating whether the targets laid down in points (c), (d) and (e) of Article 11 (2) and in Article 11 (3) have been attained:*
> *(a) Member States shall calculate the weight of the municipal waste generated and prepared for re-use or recycled in a given calendar year;*
> *(b) the weight of the municipal waste prepared for re-use shall be calculated as the weight of products or components of products that have become municipal waste and have undergone all necessary checking, cleaning or repairing operations to enable re-use without further sorting or pre-processing;*
> *(c) the weight of the municipal waste recycled shall be calculated as the weight of waste which, having undergone all necessary checking, sorting and other preliminary operations to remove waste materials that are not targeted by the subsequent reprocessing and to ensure high-quality recycling, enters the recycling operation whereby waste materials are actually reprocessed into products, materials or substances."*

The dynamic change in the operation performance of municipal waste management - divided into the three treatment categories: Landfilling, incineration, recycling and composting - was published

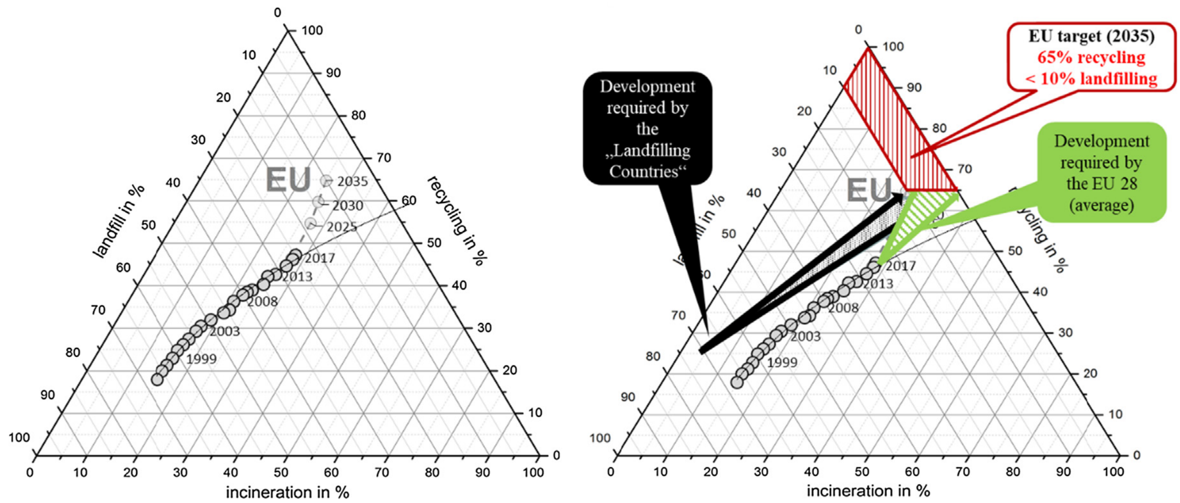

Fig. 1. Left: Development of municipal waste management in the EU 28 from 1995 to 2017 with the statistical forecasts (linear extrapolation according to the new circular economy package) until 2035. Right: Required development area of the "Landfilling Countries" and EU 28 (average) to meet the recycling targets (modified from: Pomberger et al. (2017) with currently available data in 2019).

by Pomberger et al. (2017) using the "RIL ternary diagram method". For the visualisation, information on waste amounts and their treatment was obtained from Eurostat and used as a data basis. By taking into account the data between the years 1995 and 2017 (i.e. currently available data), the following results can be shown for the individual EU Member States 28 and for the EU 28 (average) (Fig. 1): The position of performance at a specific time, the dynamic changes in performance over a certain period of time and the development trend of performance. The presentation allows countries to be assigned to one of three "groups" due to their recycling and landfilling rate: "Recovery Countries", "Transition Countries" and "Landfilling Countries". Especially for the group "Landfilling Countries", waste management still offers great potential for further development. The dynamic change in the performance of municipal waste management for EU 28 and the evolution needed to meet the recycling rates set by the circular economy package are shown in Fig. 1.

1.2. Digitalisation and intelligent robotics as modern tools for development

In order to have a common understanding of the individual terms, according to Tschandl et al. (2019), they are defined as follows.

"Digitalisation" generally describes the integration of digital technologies into everyday life. This integration is called "Industry 4.0" because it embodies the fourth industrial revolution. The English term is "Internet of Things" (IoT) and is divided into two parts: "Industrial Internet of Things" and "Consumer Internet of Things".

In the literature, as Tschandl et al. (2019) show, no uniform definition for the term Industry 4.0 has yet been established. However, the different definitions can be used to derive the following general definition: Industry 4.0 describes the widespread introduction of information and communication technology (ICT) as well as its connection to an Internet of Things, Services and Data with the goal of real-time control of production and value chain networks. Autonomous objects (workpieces, storage and conveyor systems, robots and machinery and equipment), mobile communication, real-time sensors/actuators and ICT enable a paradigm shift, from once centralized controls to a decentralized, flexible coordination of self-controlling processes. As a result, it is possible to react quickly, decentrally and flexibly to customer requirements and to produce large numbers of variants with simultaneously low batch sizes economically, as well as introduce new, customer-oriented business models successfully, which will further increase competitiveness. Every company has to find or define its own combination and roadmap for Industry 4.0

The term "smart factory" is summarized by Tschandl et al. (2019) as follows: "Individual companies or corporate groups that use ICT for product development, production, logistics and interface coordination with customers in order to respond more flexibly to incoming requests. A smart factory masters complexity, is less disruptive and enables a more efficient production. The communication between people, machines and resources is self-evident and comparable to a social network."

Digitalisation and automated work processes have already been state-of-the-art in many industry sectors for some years (e.g. automotive industry) and are mainly used to reduce the need for physically strenuous work and to make processes more efficient for human workers. In the distinction of robot types they can for example be divided into the groups: service robots (e.g. vacuum cleaner robot, lawnmower robot, pool cleaning robot, assistant robot for handicapped people, etc.), mobile robots (similar to service robots or as e.g. driverless transport robots for logistics systems, toy robots, exploration robots, etc.), humanoid robots (e.g. multifunctional machines, assistant for humans, etc.) as well as industrial robots (e.g. welding robots, painting robots, palletizing robots, mounting robots, etc.). Due to the focus on the use of the technology in plants relevant to waste management, mainly industrial robots were considered in this contribution. These differ mainly in the type of kinematics (serial or parallel), in the load, in the acceleration and speed, in the repeatability, in the gripping system and in the reachable working range (Dokulil, 2001; Shah and Pandey, 2018).

Especially in the industry-sector so-called collaborative robots ("Cobots"), which are specially designed to work with people in the immediate or same work environment, gain more and more importance. Cobots are for example used to end a work process started by a human worker, or vice versa. An important factor in using Cobots is the concept of a shared workplace. In order to make this possible, a reduction in the speed and power of the robot arm is necessary, as well as the additional equipment for the robot with special sensors that detect the position of people present and are able to respond accordingly (TÜV Austria Group and Fraunhofer Austria Research GmbH, 2016). Examples of Cobots include the lightweight robot "iiwa" ("intelligent industrial work assistant") and the model "LBR iisy" from KUKA, the model "YuMi" from the manufacturer ABB, and the models from Festo (ABB Robotics, 2019; Festo, 2019; KUKA, 2019).

According to statistics from the IFR - International Federation of Robotics (2018), 2017 was a record year in the installation of robots in the automated manufacturing industry: on average, 106 new robotic units were installed per 10,000 employees in Europe. The leaders in the global ranking were South Korea with 710 robots, Singapore with 658 robots and Germany with 322 robots per 10,000 employees. In total, around 381,300 robotic units were sold worldwide in 2017, which represents an increase of 30% compared to the previous year. The fastest growing use of robots is shown in Asia and Australia, but growth is also evident in Europe and America (IFR - International Federation of Robotics, 2018).

1.3. Digitalisation and intelligent robotics in the value chain of circular economy oriented waste management

The comparison of waste management with other industrial sectors shows that digitalisation and the use of robots in circular economy and waste management are still in their infancy. However, as the digitalisation and approaches of Industry 4.0 are rapidly developing in all sectors, more and more applications for the aforementioned technologies are emerging especially for use in waste management. Surveys by NETWASTE concluded that the topic of e-commerce already has a high priority for many waste disposal businesses. Companies use waste portals on the internet, are represented on various platforms for social media or make their own apps available to customers. In the future, digitalisation in waste management is estimated to be relatively high. The use of electronic invoices, paperless order execution and the use of service portals will be estimated at over 60% in the future. The extent to which the use of systems for live container tracking and digital container detection, or the use of robots for waste collection and sorting, to self-automated containers and collection vehicles will be relevant for the future is for the most part still unclear. However, at least 30% of the respondents see a great importance in the future of the points mentioned (Mechsner, 2017). For this article, technologies of digitalisation were specifically investigated for the use in the so-called "Smart Waste Factory Network" (SWFN4.0). The given definition from Curtis and Sarc (2018) is part of the *ReWaste4.0* project and defined as follows:

> *"The SWFN4.0 describes a system consisting of several waste treatment plants, which perform different tasks in the waste management system and are interconnected via data streams and logistics systems (e.g. sorting plants, production plants for Solid Recovered Fuels, etc.). The individual processes and machines within the plants as well as the individual plants are digitally connected with each other. This connection of the individual machines and systems and the real-time analysis of the waste streams enable dynamic process control and various actuator systems actively intervene in the processes. In addition, people can cooperate interactively with the technology around them."*

Subsequent chapters explain and discuss the procedure for developing the article and the objectives and results pursued. Section 3 is divided into the five main focuses:

Section 3.1 focuses on "smart bins" (e.g. waste collection containers equipped with sensors for material detection or level measurement), self-automated containers and vehicles, and methods for automatic image analysis. Section 3.2 mainly deals with the sorting of waste by robotic technologies and compares systems from different manufacturers on the market. In addition, the data- or model-based optimized operation of treatment plants is discussed. The topics of digital communication, which makes it for example possible, to order container systems for disposal via internet platforms, predictive maintenance and product as a service are covered in Section 3.3. In order to simulate or carry out processes in waste management plants, large amounts of data are needed as a basis. In terms of material quality in particular, metrological recording (in real-time) represents a major challenge. Methods for utilizing this data, such as for example Blockchain Technology, Deep Learning and multivariate model equations are discussed in Section 3.4. Finally, the results of an online market survey about digitalisation and Industry 4.0 of companies relevant for the waste management sector will be presented (see Section 3.5).

Furthermore, the present article compares the examined topics in a scientific summary and gives an overview of future applicable technologies, which contribute to the further development of circular economy in the waste management sector. The economic importance of this topic was discussed in a study about "Digitalisation in the Green Tech Industry" by Berger (2016), where a global amount for the sector circular economy/waste management was estimated at around 170 billion euros (€) for the year 2025.

2. Materials and methods

The aim of this contribution is to capture the developments and opportunities in waste management about digitalisation and intelligent robotic technologies as far as possible (or almost completely), to investigate them professionally and to present them in a "scientific review". In particular, the aspects that contribute to digitalisation in the value chain of circular economy oriented waste management are brought into focus. The procedure which led to the following results included the following steps:

- Market survey, with approx. 400 evaluable feedbacks,
- Definition of the four relevant topics in the value chain in waste management:
  1. Collection and logistics,
  2. Machines and waste treatment plants,
  3. Business models and
  4. Data tools.
- Extensive survey of national and international publications and information in the period 2001–2019 and assignment to the relevant topics in the value chain. In total, more than 80 relevant publications are discussed in the present article (see Figs. 2 and 3),
- Carrying out the intense analysis of the figures, data and facts found for the area waste management.

Within the framework of the K-Project *ReWaste4.0* - as already mentioned before - an online market survey of companies from the waste management and waste disposal industry on the topic of digitalisation and waste management 4.0 was performed. The online survey was conducted by means of a questionnaire with nine questions. The survey was by an e-mailed online survey carried out on 2350 companies of various sizes from the fields of waste management and recycling technology in the DACH-region (Germany, Austria and Switzerland). In total, 394 companies completed the questionnaire and responded to us, which corresponds to an evaluation rate of 32.5%. The questions with answers and additional company comments from the survey are presented in detail by Sarc and Hermann (2018) and summarized as part of this article in Section 3.5. From the results obtained, the four segments for the value chain mentioned above were defined.

The contributions of the literature were established via databases with the following relevant search terms (keywords): "digitalisation", "robotics", "smart waste", "smart factory", "industry 4.0", "internet of things", "waste management" and

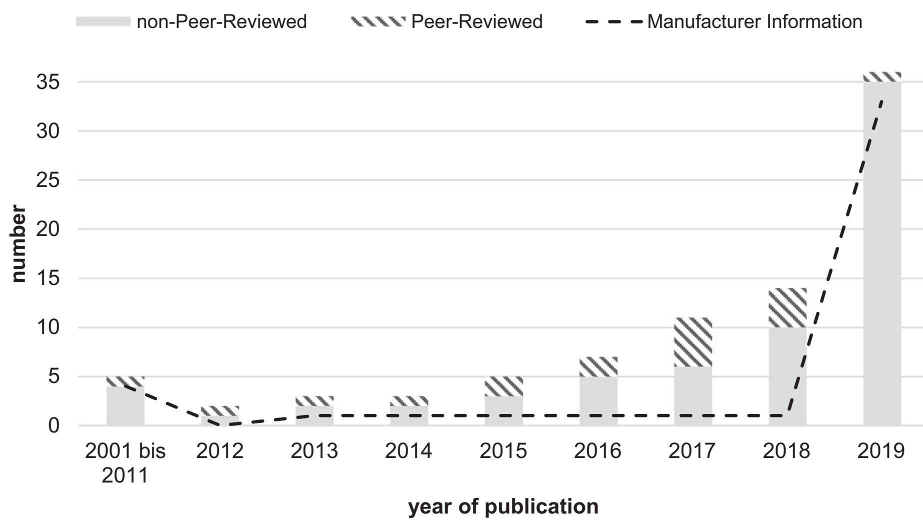

Fig. 2. Number of reviewed literature sources by type, assigned to peer-reviewed or non-peer-reviewed papers over the years 2001–2019.

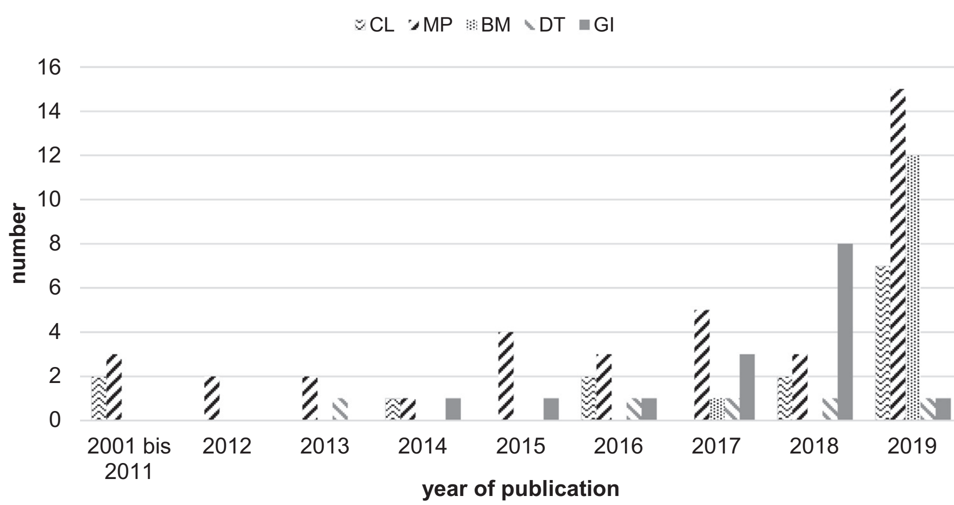

Fig. 3. Type of source (see Fig. 2) assigned to the priorities covered therein over the years 2001–2019. *Note:* CL - Collection and logistics, MP - Machines and waste treatment plants, BM - Business models, DT - Data tools, GI - General information.

"circular economy". These search terms were used individually and in all possible combinations for the search. For the evaluation of the results of this scientific contribution, relevant publications could be found over the period from 2001 to 2019, although the majority are from the last three years (2017 to date). In addition, detailed research was conducted on existing technologies in the environmental field, with a focus on waste management (Kandlbauer, 2018). The information and applications gained were in turn assigned to the four previously defined value chain segments. In the research, especially the areas of digitalisation, (intelligent) robotic technologies and Industry 4.0 came to the fore. The following Figs. 2 and 3 compare the results of the research carried out. A total of 115 sources could be utilized. It should be noted that only sources with content relevant for waste management were considered in the graphics, resulting in a total of 85 relevant literature sources. In addition, legal regulations were used for drafting the contribution, which are not considered in the illustrations shown. The figures show that the topics digitalisation and intelligent robotics in waste management, have yet not intensively been discussed in peer-reviewed papers and most of the information comes from technology- and platform-manufacturers (websites, brochures, etc.).

As shown in Fig. 2 the number of entries in/from 2019 compared to the years before is particularly high, as the literature research for the finalisation of the present paper has taken place this year and much information (especially from the manufacturers' websites) has been used. These sources are all considered in 2019 unless stated otherwise. In order to keep the information regarding the number of existing sources meaningful, manufacturer information was considered separately. When interpreting the chart, note that all manufacturer information is reported as non-peer-reviewed. In the next step, the found sources (i.e., Fig. 2) have been assigned to the thematic emphases (i.e. value chain segments), cf. Fig. 3.

As shown in Fig. 3, from 2001 to 2018, the topics CL and MP were predominantly examined, while nowadays (2019) the focus is on BM with digital platforms and product as a service approaches.

3. Results and discussion

"Big Data" is a fundamental element of digitalisation and already a valuable raw material for many industries. In combination with "Artificial Intelligence", it is possible to structure, analyse, evaluate and use large amounts of data as a basis for

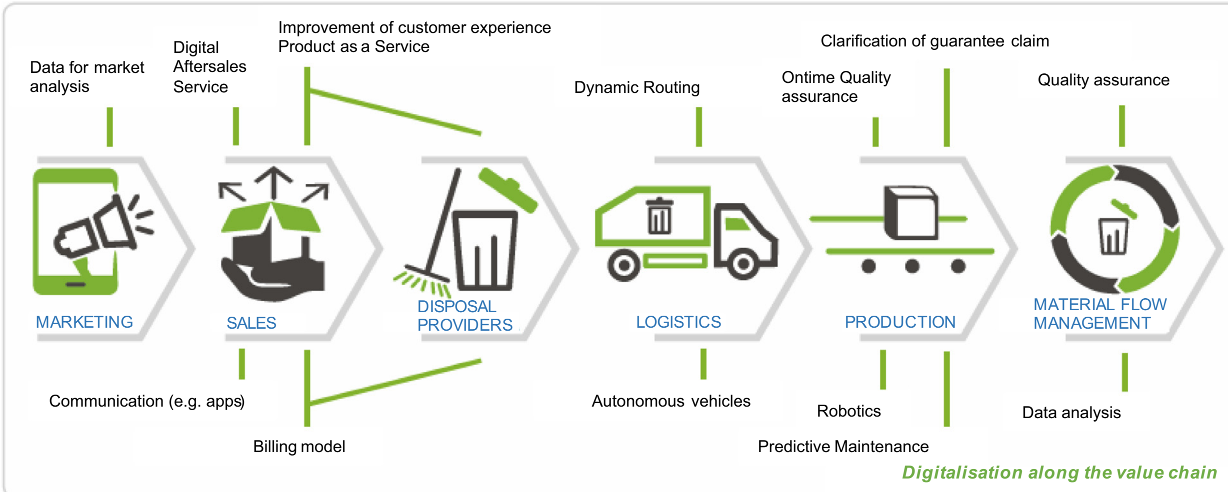

Fig. 4. Digitalisation along the value chain (Green Tech Cluster, 2018a).

software programs that can generate new (or extended) knowledge with the technology of "Machine Learning". From this, future forecasts can be derived as well as used in optimization measures. Often "Deep Learning" is used, which is based on the human brain and uses artificial neural networks to mimic the learning processes of humans. This makes it possible to use data volumes meaningfully across the entire value chain (see Fig. 4).

Just like in other industrial sectors, the use of digitalised systems in waste management is becoming increasingly interesting and, as a driver of innovation, is opening more and more opportunities for businesses: robotic systems learn from experience and can sort more efficiently. In addition, the speed of the conveyor belts can be independently controlled by means of self-learning machines. Great opportunities are seen for disposal companies, especially in the field of logistics through route optimization, as well as intelligent collection containers. The US company ecoATM shows how efficient recycling of old mobile phones could work with the device "electronic waste ATM", which is similar to an ATM: The machine checks the old mobile phone to the value of the device, determines the reusable raw materials contained and pays the same value to the customer (ecoATM, 2019). This principle would also be conceivable for other existing waste materials.

At present, digital availability ("readiness") in waste management companies of German-speaking countries is only 30% (Berger, 2016), which leaves big opportunities for these companies to use digitalisation. The global demand for "green products" and acceptance of the basic idea of a green economy is increasing. This expansion is also reflected in the market volume: In 2013, the global market volume amounted to 2536 billion euros. By 2025, an increase of up to 5385 billion euros (€) is predicted. Of this, around 100 billion euros (€) were spent on the circular economy in 2013. This amount will rise to 170 billion euros (€) by 2025 (Berger and Büchele, 2014).

An important aspect that must be considered when using industrial robots is the safety requirement for systems and machines located therein, where the legal framework of the Machinery Directive of the European Council (Directive 2006/42/EC) must be taken into account. Here, are amongst others, the following standards are relevant: EN ISO 10218-1 (requirements for industrial robots), EN ISO 10218-2 (design specifications and requirements for the robot system), ISO/TS 15066 (robots and robotic devices - collaborative robots), EN 12100 (Safety of machinery - Risk Assessment and Risk Mitigation), EN 13849-1 (Safety Related Parts of Controls Part 1), EN 13849-2 (Safety Related Parts of Controls Part 2).

In principle, industrial robots are rated with a high security risk, with the result that protection concepts are designed in such a way that humans and robots work separately in terms of time and/or location. In order to differentiate the work area of a robot, both mechanically separating (grids, fences) and non-separating installations (laser grids, laser scanners) are used. This can lead to greater space requirements and additional costs due to the necessary structural facilities. Newer concepts put so-called human-robot-collaborations in focus. These are designed in a way that people and robots work directly together without guards, and machines support people with their abilities. (TÜV Austria Group and Fraunhofer Austria Research GmbH, 2016). In addition, it must be borne in mind that the connection and networking of robots or actuator systems with the internet must also increase security measures against cyber-attacks (IT-security). Especially with robots, which can be controlled by employees via remote maintenance, increased safety concepts are necessary. The relevance of security to cyber-attacks on industrial robots was examined and published in a 2017 Trend Labs report (Maggi, 2017). In the present article, no further, more detailed explanations about safety-related requirements are considered, since, as already mentioned in Section 2, four relevant value chain segments in waste management are the focus of the current investigation which are presented and discussed below.

3.1. Waste collection and logistics

In recent decades, waste management has evolved from a pure logistics industry to a manufacturing industry due to the ever-increasing volume of waste and the trend towards recycling. Nevertheless, logistics continues to be an important means of linking the waste management sector with the rest of the industry. Ongoing new technical possibilities through digitalisation make it possible to optimally further develop logistics in waste management. There are already various approaches, which are explained in more detail in the following sections of the article. In addition, several peer-reviewed papers have already been published which deal with the topic "Collection and logistics of waste" in so-called "smart cities" (Anagnostopoulos et al., 2017; Esmaeilian et al., 2018; Rovetta et al., 2009; Shah et al., 2018).

3.1.1. Smart bins and level measurement

There are different approaches and designs in the field of "smart bins". Various manufacturers equip containers with sensors capable of detecting levels to make disposal more profitable (Bigbelly Solar, 2019; Binando, 2019; E Cube Labs, 2019; Enevo, 2019). In households, smart speakers like "Amazon Echo" or "Google Home" spread quickly and provide a convenient way to gather information. For example, Simple Human (2019) offers a trash can, which can be opened and closed with voice control or hand gestures. In addition, further development in terms of customer advice for waste classification, or independently find and propose suitable disposal solutions could be a future option. Furthermore, the development of autonomous robots for waste collection brings another possibility. The first research projects focused on autonomous robotic solutions for waste collection already in 2006: The DustBot project focused on the development of autonomous systems from 2006 to 2009 with the aim of improving the urban hygiene and waste management of European capitals. In the course of the project, different autonomous cleaning robots for the streets (DustClean) were developed, as well as mobile robots with user-friendly design (DustCarts). Customers can order DustCarts to desired addresses, where they pick up smaller amounts of household wastes and bring them to a corresponding waste collection centre (DustBot, 2006).

A more recent research project was initiated in 2015 under the collaboration of the Swedish car manufacturer Volvo and the German waste management company Renova. A self-propelled, mobile robot ("ROARy") was developed, which is able to find garbage cans in the area and transports them to a collection vehicle. The first prototype has been around since mid-2016. The emptying of containers works in such a way, that a drone searches for waste bins in the area and sends the corresponding coordinates to the robot. The robot is attached to the collection vehicle and is able - with the help of the coordinates, sensors and cameras - to find the bin, pick it up, transport it to the collection vehicle and return the empty container. At the moment, Volvo does not see the project as mature, because it is too slow to actually be used. The project leader says "... the project is intended to stimulate imagination and test new concepts that can influence new transport solutions of the future" (Robarts, 2016; VolvoGroup, 2016).

Other companies have developed collection systems with integrated material detection sensors, allowing separation into different fractions. The French manufacturer "Green Creative" presented a waste bin named "R3D3" in 2016, which collects beverage packaging (PET bottles, metal beverage cans and coffee cups) in separate compartments within the container (Green Creative, 2019). Also, the Polish company "Bin-e" offers a device with similar functionality. In addition, according to the manufacturer, the Smart Bin is equipped with Artificial Intelligence and Deep Learning function and sends the determined material data to external databases, which can then be downloaded to other waste bins from the same manufacturer, thus improving the identification of materials. The networking of the waste bin also allows disposal companies to be informed about the filling level of the individual containers (Bin-e, 2019). According to the manufacturer, the target groups of the two products are offices, large households, airports, shopping malls, etc.

3.1.2. Vehicles

Autonomous vehicles are often used in industries, especially in mining (Komatsu, 2019; Liebherr-International Germany GmbH, 2017; Sandvik, 2019; Volvo Germany, 2019; Volvo, 2019) and are gaining even more importance in passenger transportation (Tesla, 2019). Especially for waste management, a project for an autonomous collection vehicle was started. The cooperation between the car manufacturer Volvo and the waste management company Renova has adapted the concept of the self-driving Volvo FMX truck for mining operations, which has been tested in mines in northern Sweden since 2016. Practical tests have also been carried out for the driverless collection vehicle. The truck no longer needs a driver, because the route is pre-programmed and the fact that the vehicle is equipped with sensors and cameras allows the truck to take moving obstacles into account and avoid them. The driver has the task to bring the full waste bins to the vehicle and to empty them. Via a control panel at the rear of the vehicle, the driver can continue or interrupt the route of the vehicle (VolvoGroup, 2018).

The lack of acceptance of new technologies by users is unlikely due to the rapid technological development. However, in the introduction of (semi-)autonomous disposal vehicles and containers, obstruction might be unresolved legal issues, such as for example liability issues when accidents are caused. In addition, there are already initial considerations and concepts for how underground disposal can be used in future smart cities (Alphabet, Sidewalk Labs, 2019). At the moment, however, this option is not economically viable.

3.1.3. Routing

- The topic of routing in waste management was scientifically discussed and researched in detail in the following contributions, which are listed below with summarized findings. Hannan et al. (2015): This review article deals with information and communication technology and their usage in the waste management sector (e.g. identification technologies, data communication technologies, routing, real time bin status information, etc.).
- Mes et al. (2014): The contribution considers "inventory routing" for dynamic waste collection.
- Ramos et al. (2018): The article reviews different approaches for implementing dynamic routing and gives overall information about the use and benefits of real-time data in the waste management sector.
- Rossi et al. (2018): The paper discusses routing of autonomous vehicles in transportation networks with various model systems.

3.1.4. NFC/RFID tags in products and trash button

This topic (NFC: near-field communication, RFID: radio-frequency identification) is discussed in the article by Hannan et al. (2015) (RFID as bin and driver tracking) and is also already used in combination with an application for mobile phones, to commission disposal services (Zentek, 2019).

3.2. Machines and waste treatment plants

In many industry sectors, plant components have long been connected and control each other because they e.g. react on pressure and/or temperature gradients (e.g. Chemical industry). In the waste management sector, this connection has not fully enforced yet. The reason for this is the heterogeneous composition of waste streams, which makes the (real-time) modelling of work processes and especially the status detection of the material flows (quality assurance) more difficult. With advances in technology and the increasing demands (e.g. purity) on recycled materials, there are increasing opportunities to implement Industry 4.0 approaches in different ways in plants relevant for waste management.

Waste management systems often consist of a combination of complex individual machines. For their interaction, however, very simple control mechanisms are frequently relevant, which can be measured by means of a few system parameters (e.g. starting of the conveyor belt takes place when the level sensor on the unit gives a signal). In the future, digitalised waste treatment plants will be controlled dynamically, as many different sensors will provide information about the operating status of a plant. Additionally, the status of the material flow at the input in the plant and after each treatment step will be detected via information about the qualities, mass and volume of the individual material flows. Machine-to-Machine (M2M) technology will also be used to allow machines to optimally configure each other. Due to the large number of waste streams, the optimal treatment results in a variety of processes which have different influenceable process parameters. The on-line/on-time characterisation of the quality of the material flows takes account of corresponding information in the control of the plant or aggregates, which regulates itself accordingly. In addition, research on new sensor technologies (mid-infrared (MIR), laser-induced breakdown spectroscopy (LIBS), terahertz) will make a major contribution to make sorting into individual material fractions possible (especially for materials difficult to detect, such as black plastics) or determine the composition of objects at the particle level. Similarly, robotic technology will play an important role in waste sorting. The combination of object recognition, multivariate statistical modelling approaches and Deep Learning tools will be used for tasks that are too dangerous or too stressful for humans (Green Tech Cluster, 2018a).

Furthermore, innovative (intelligent) safety installations for waste treatment plants will also be interesting. Especially in recent years, more and more fires occurred in treatment plants, because a higher amount of fire-promoting waste (e.g. lithium-ion batteries) occurs in waste streams (Nigl and Pomberger, 2018). Gundupalli et al. (2017a) have published an article which covers technologies for automated sorting of mixed waste, but they don't put focus on robotic technologies.

3.2.1. Volume- and mass flow measurement incl. sensors

In most waste treatment plants, mass flows are measured into and out of the plant by weighing the arriving and departing vehicles by means of a weighbridge. The weighing data is usually obtained with great delay only and the input and output currents are always buffered via bunkers. In many cases, the shovels of wheel loaders are equipped with weighing devices, so the system throughput can roughly be determined. However, these methods do not allow the control of a plant, as all important mass flows would have to be recorded in real time. There are many systems on the market that use a variety of physical principles that allow real-time measurement. In the industry, the following measuring systems are used: belt scales, impact plates, radiometric measurement, operating time measurement (ultrasound, laser), laser triangulation, etc. Not all systems are suitable or desired for the use in waste treatment plants for various reasons (including cost, accuracy and radiation protection). The retrofitting of weighing belts is often not possible due to the limited space. Many waste fractions (e.g. plastic foils, etc.) have a very low bulk density and therefore cannot be measured accurately. The value added in the treatment of mixed non-hazardous waste is very low and therefore expensive systems such as e.g. radiometric systems (including the employment of a radiation protection commissioner), laser systems, etc. are not enforced until now. In waste management, quantities are expressed in masses (i.e. tonnes). On the other hand, there are systems that measure the operating time of emitted signals as well as laser triangulation, which calculates volumes and volume flows. In order to be able to convert these volume flows to mass flows, it is necessary to know the bulk density of the material. However, it is not constant in time or in the course of the preparation process and would have to be measured continuously in order to calibrate the system in real time and to obtain the resulting mass flows. The retrofitting of a system with volumetric flow measuring systems is much easier since the necessary measuring beams equipped with the measuring technology are simply mounted over the respective conveyor belts. One way to perform a rough density calibration would be to recognize the material through images via Machine Learning using material density databases.

An example on the significance of material flow management in waste treatment plants is given by Feil et al. (2019). They present a sensor-based process control concept to achieve a continuous material flow, which should result in optimal conditions for further treatment in the plant (e.g. classifying, sorting).

Currently leading manufacturers in the field of sensor-based sorting in Europe are Binder + Co AG (2019), BT-Wolfgang Binder GmbH (2019), Pellenc ST (2019), Steinert Elektromagnetbau GmbH (2019) and Tomra Systems GmbH (2019). The mentioned companies offer the sensor technologies listed in Table 1 (amongst others) for different applications.

Especially for the use in sorting with robotic technologies, a 3D perception sensor was designed by the start-up roboception. Together with the German robot manufacturer KUKA, the KUKA_3D Perception Sensor was developed, which is able to create 3D recordings in real time and can record the positioning in the room. In addition, there is the possibility to perform different "bin-picking" applications with the sensor using manufacturer software (KUKA, 2019).

3.2.2. Image evaluation

Currently the Chair of Automation at Montanuniversitaet Leoben is doing research on imaging combined with Deep Learning to enable the automatic classification of waste in processing plants. The goal is to be able to classify the type, contents and state of waste prior to or during processing. This classification should enable the automatic parameterisation of the waste processing

Table 1
Overview of sensor technologies (Pomberger and Küppers, 2017; Flamme et al., 2018).

Sensor	Separation criteria	Scope of application
VIS[a]	Colour	Glass, Paper-Cardboard-Cardboard Packaging, Plastics, Metals
NIR[b]	Chemical composition	Paper-Cardboard-Cardboard Packaging, Plastics, Wood; problematic for black plastics
XRT[c]	Density	Plastics, Metals, Inert fraction from construction sites, Wood
XRF[d]	Elemental composition	Metals, Plastics (PVC)
EMS[e]/inductive sensor	Electrical conductivity	Metals
MIR[f]	Chemical composition	Black Plastics
Terahertz-spectroscopy	Chemical composition	In research
LIBS[g]	Chemical composition	Aluminium-alloys, Plastics, Wood

[a] Sensor with spectrum in the range of visible light.
[b] Near-infrared.
[c] X-ray-transmission.
[d] X-ray-fluorescence.
[e] Electromagnetic sensor.
[f] Mid-infrared.
[g] Laser induced breakdown spectroscopy.

equipment to obtain better and hopefully near-optimal performance.

The approach is to acquire images of the waste in situ using industrial cameras and to apply Deep Learning to automatically generate classifications pertaining to the content, type and state of the waste. Deep convolutional neural networks (CNN) can be considered in several different layers; the lower layers detect primitive features in the images. This task is highly generic; consequently, it is possible to use pertained networks (PCNN) for these layers. This is known as transfer learning, since it is transferring the neural coefficients which are required to detect primitive features in the images, from other applications. The upper layers are then trained to identify the presence of the classes' specific to the application at hand as combinations of the primitive features. These PCNN have the advantage of saving training time, while simultaneously requiring fewer images to obtain a successful convergence of the trained network.

To date, studies on methods for digital image analysis have been published by Bonifazi et al. (2018); Gundupalli et al. (2017b) and Wagland et al. (2012).

3.2.3. Waste sorting

Many industrial robots are commonly used to perform assembly line operations with very precise but equal sequences, which requires data-based pre-programming. The challenges of using robotic technologies to sort waste are the heterogeneity and surface contamination of the waste streams, the inconsistent shapes or masses that must be grabbed, and the random location of the objects in the waste stream. Furthermore, it is considered to be problematic that the positions of the particles or objects on the conveyor belt can change by vibrations or the draft (arising by the movement on the conveyor belt). The resulting problem is, that the detected position changes and the actuator (e.g. robot arm) grabs "into space" and the object is ultimately not sorted out.

For waste sorting, the processes for material or object recognition with the associated algorithms and the software in the background are of great importance. If this software is combined with suitable hardware and an additional implementation of Artificial Intelligence is carried out, robotic systems are able to fulfil multitasking tasks and thus perform several sorting tasks at the same time. If necessary, new fractions can be "trained", making the technology very future-proof in terms of changing waste streams. The robots used in some cases replace human sorters and/or find application in areas (e.g. construction site wastes) that have not been sortable until now and/or allow automatic quality assurance and enhancements (e.g. plastics). Especially in the area of construction and demolition waste, the use of robotic technologies for sorting is very interesting, as the sorting by humans is restricted on the one hand by the limited object size (with regard to weight) and on the other hand by the dust produced during processing (including asbestos) (AMP Robotics, 2019; BHS, 2019a, 2019b; Kujala et al., 2016; Lukka et al., 2014; ZenRobotics, 2019). In some cases, pre-shredding of the material up to a certain particle size is necessary. The developers of robotic technologies do not see robotic waste sorting in all areas as a future solution. Especially in the area of municipal solid waste (MSW), in particular, packaging waste, many manufacturers see the combined use of robotic technologies and optical sensor sorting systems with pneumatic discharge as the ideal solution for the future. Often, the automated devices are also found as a quality assurance system at the end of the sorting system to monitor the output flow from a plant.

Various research projects have been involved in the development of robotic technologies for the sorting of radioactive waste in the past. Mainly human-controlled robots have been used to perform certain work in radiation-contaminated areas. Two recent European research projects focused on the development of a modern robotic system for the sorting of nuclear waste. In the project RadioRoSo ("Radioactive Waste Robotic Sorter"), a system with automatic or semi-automatic sorting by dual-arm robots and robotic cranes was developed (ECHORD++, 2016). The project RoMaNS ("Robotic Manipulation for Nuclear Sort and Segregation") also dealt with the same topic. The focus was on the development of novel hardware and software for remote-controlled robots as well as the programming of automatic gripping gestures and algorithms to automate robot movements (European Commission, 2015; University of Birmingham, 2015).

Researchers at the Danish Institute of Technology (DTI) have been working on the development of a robotic-based system that uses Artificial Intelligence to sort hazardous waste as part of the AAWSBE1 (Adaptive Automated Waste Electrical and Electronic Equipment Sorting Battery Extraction) project. The focus is on the sorting of batteries in electrical devices. Therefore, it is necessary to detect devices that could contain batteries, but also to detect individual batteries in material flows. The system works with signals from different cameras and Deep Learning technology (ECHORD++, 2012).

As an example of material recycling of a very specific material group, the concrete recycling robot ERO can be mentioned, which allows the automatic demolition of concrete walls (ERO, 2019). The electronics manufacturer Apple has also developed a robot for a very specific recycling process. The two projects LIAM and DAISY focus on the recovery of selected materials (mainly metals) and their return to the raw materials cycle. Launched in 2016, LIAM was developed for the deconstruction of iPhones and consists of a chain of 29 individual robots, which successively disassemble old iPhones and remove a total of eight components from the device (including: display, battery, motherboard, speakers, camera, housing, etc.). This is achieved by special suction devices, drills, attachments as screwdrivers and heating devices to solve adhesive joints, etc. Furthermore, complex safety devices are installed, which interrupt the process when the development of heat caused by the battery is to strong (Rujanavech et al., 2016). At the end of April 2018, DAISY - as a successor to LIAM - was introduced by Apple. The recycling robot is now able to disassemble different iPhone models into its individual parts, which was not possible with the first robot and criticized. Now, the disassembling process for one unit just under 20 s are needed, which leads to a maximum capacity of 200 iPhones per hour (Heater, 2018).

The following subsequent subchapters (i.e. Sections 3.2.3.1 to 3.2.3.7) present several systems for waste sorting designed for mixed waste streams.

3.2.3.1. ZenRobotics heavy picker. ZenRobotics company, based in Helsinki, Finland, was founded in 2007. Based on the sorting of construction and demolition waste, the ZenRobotics Heavy Picker was developed in 2009 and since then has been continuously improved. The system is equipped with gripper arms and can sort out contaminants, as well as recyclables from mixed waste streams with the help of Artificial Intelligence. The number of fractions to be sorted is unrestricted (in principle) and can be continuously extended during operation. The "training" of a new fraction is done with desired sample fractions. The system consists of different sensors, a control unit and industrial robots (see Fig. 5). The waste is on a conveyor belt which moves under the robotic arm at a speed controlled by the robot. In operation, the sensor unit scans the material which is analysed by the specially programmed control software. In addition, the software has the task of controlling the robots, as well as identifying the materials of the waste and the gripping points. With these calculated gripping points, the pneumatic operated gripping arm (see Fig. 5) grips the corresponding object and sorts it into the respective fraction while taking the

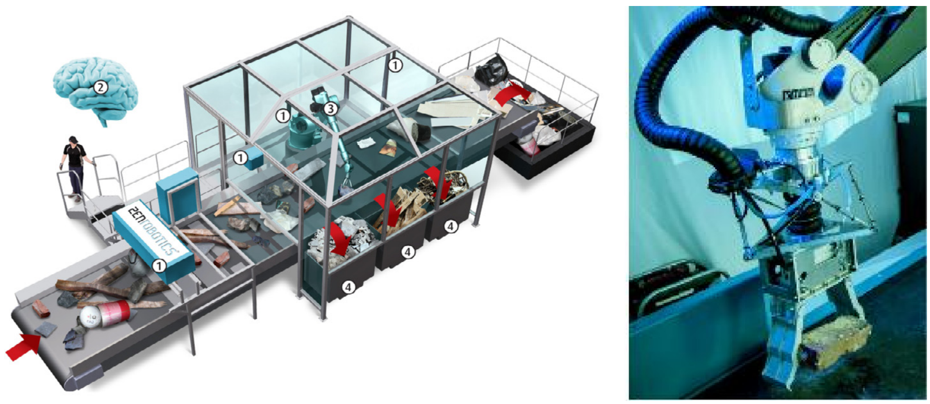

Fig. 5. Left: Scheme of ZenRobotics "Heavy Picker", 1: Sensors, 2: Control unit ZenRobotics Brain, 3: Industrial robot arm, 4: Containers for sorted fractions; Right: ZenRobotics "Smart Gripper" (Lukka et al., 2014).

trajectory parabola under consideration (Lukka et al., 2014; ZenRobotics, 2019).

To identify the objects and their materials, the system uses different sensors and cameras (VIS-, NIR-, metal-, 3D-laser sensors, RGB cameras), which send data to the control software. There the combination of Artificial Intelligence and Machine Learning algorithms are able to identify the individual objects form the data and determine the optimal gripping sequence from so-called "handles" (Burkowski and Lukka, 2011, Burkowski and Rehn, 2015, Lukka and Borkowski, 2011, Lukka and Kujala, 2017, Valpola, 2011).

A single robotic arm is capable of sorting out up to four different fractions simultaneously. Currently, ZenRobotics customers are sorting construction and demolition waste, industrial waste, metals, wood, hard plastics, and bags by colour. The tangible objects are limited to a maximum weight of 30 kg and maximum dimensions of 1500 mm by 500 mm. The gripper arm is capable of 2000 picks per hour. If necessary, it is possible to connect several robot arms in succession to increase the output of the plant (ZenRobotics, 2019).

The following reference companies are mentioned by the manufacturer: Finland (Remeo, Viikki), Sweden (Carl F., Malmö), The Netherlands (Baetsen), Switzerland (Eberhard, Zurich), Japan (Shitara, Daitou), Australia (Sunshine Groupe), France (Veolia), China (LVHE Environmental Technology) and USA (Recon Services Inc., Texas). Mainly construction and demolition waste are sorted, whereby the sorting is carried out by the robotic system alone or also in combination with human workers for pre-sorting (ZenRobotics, 2019).

3.2.3.2. SELMA. The Swedish company OP-teknik specialises in automation technology and has developed an automatic sorting system called SELMA, together with the German machine manufacturer Doppstadt. The robot arms used are multi-axis robots from the Japanese manufacturer Yaskawa and can, as shown in Fig. 6, be connected in series in the system. Each arm with the mechanical gripper creates up to 2400 picks per hour. With a recommended combination of the manufacturers of six arms, this results in 14,400 picks per hour. The system can also be set up and transported as a mobile unit in a container (see Fig. 7, right). According to the manufacturer, the system can be used to sort various materials, including wood, stone, concrete, bricks, metals, cardboard, foam, plastics, polystyrene, etc. (Doppstadt, 2019, OP teknik ab, 2019).

3.2.3.3. ZenRobotics Fast Picker. The ZenRobotics Fast Picker has also been developed by the Finnish manufacturer ZenRobotics and is a system which, in contrast to the ZenRobotics Heavy Picker, does not specialize in sorting heavy construction and demolition waste but rather smaller and lighter materials. This allows use in the area of packaging waste or mixed municipal waste (see Fig. 8). The gripping of objects takes place via a suction cup. In sorting plants, the Fast Picker can be used as a quality assurance system. The robot is controlled by a software, which uses Artificial

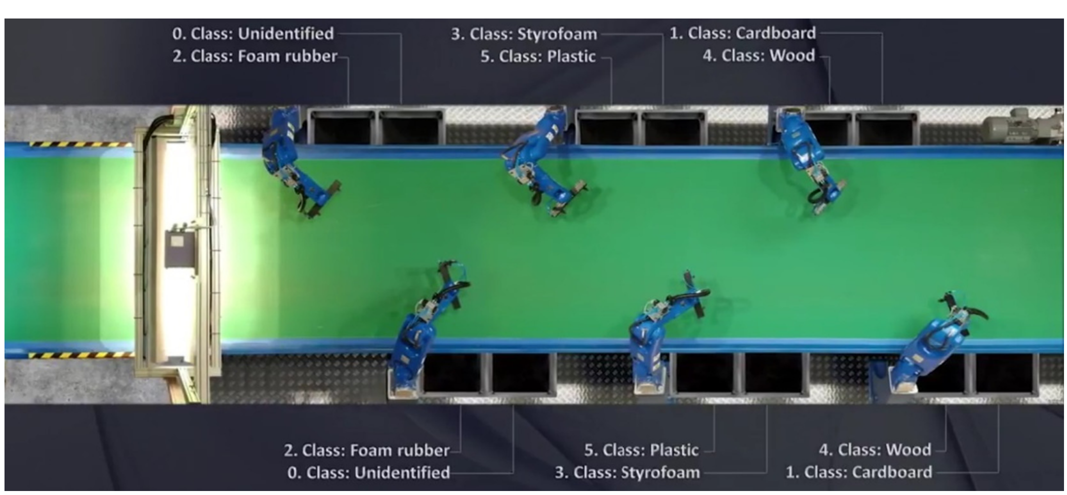

Fig. 6. Scheme of the SELMA sorting system (OP teknik ab, 2019).

Fig. 7. Left: Gripper of the sorting system, Right: Mobile unit mounted in a container for easy transportation (OP teknik ab, 2019).

Fig. 8. ZenRobotics Fast Picker with focus (right graphic) on actuator with vacuum gripper (ZenRobotics, 2019).

Intelligence for the analysis of the data and control of the function. Through the software, new material data can be constantly acquired and saved in order to further optimize future sorting. The maximum weight of the sortable objects is limited to 1 kg, the maximum dimensions are 400 mm. The vacuum gripper can handle up to 4000 picks per hour (ZenRobotics, 2019).

3.2.3.4. MAX-AI AQc. The company BHS (Bulk Handling Systems) from Oregon, USA, presented its first sorting robot for waste in 2017. Together with the technology company Sadako from Spain and National Recovery Technologies (NRT) from Tennessee, a sorting robot was developed, which works with Artificial Intelligence and is used as a quality assurance system. The Max-AI Autonomous Quality Control (MAX-AI AQC) robot uses ABB's delta robot (FlexPicker) as the basis (Paben, 2017; Sadako Technologies, 2019). Artificial Intelligence is achieved through Deep Learning, and the sorting process is based on the evaluation of optical data, which is determined solely by VIS-sensors. The installed software is able to recognize recyclables and other objects that can be recycled and to separate up to six different fractions at once (BHS, 2019b). The system is designed in a way that a gripper arm with suction cup is mounted above the conveyor belt and separates the identified objects from this position into lateral outlets (see Fig. 9). According to the manufacturer, the MAX AI AQC is able to achieve 65 picks per minute (3900 picks per hour) (BHS, 2019a).

The first facility of the MAX AI AQC was commissioned in 2017 in Sun Valley, California for the Athens Services Material Recovery Facility. At this site, the robot is used as part of a fully automated PET sorting system. Similarly, a plant in Pennsylvania (Penn Waste), as well as a plant in San Jose, California (Green Waste) use the sorting system for the same task. According to National Recovery Technologies (NRT, Tennessee, USA), more than 40 orders are placed in four continents. The European subsidiary of BHS is based in Amsterdam (Nihot) (BHS, 2019a, 2019b).

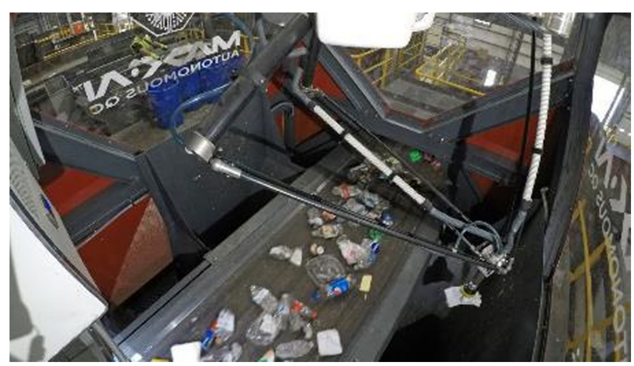

Fig. 9. MAX-AI AQC in operation (BHS, 2019a).

3.2.3.5. Cortex. In March 2017, the "Cortex" sorting robot from AMP Robotics with Artificial Intelligence was presented at a waste treatment plant in Denver. The development was performed with the Carton Council of North America and Alpine Waste & Recycling and focused on sorting packaging waste. The Cortex system, which got the nickname "Clarke", also uses a delta robot of the company ABB (FlexPicker) as a basis (see Fig. 10). The system works with VIS-sensors and performs the evaluation using Machine Learning. In addition, the system is connected to a database in which all information on detected materials is saved. During sorting, speeds of up to 60 handles per minute (3600 picks per hour) can be achieved (AMP Robotics, 2019).

Known waste sorting plants using the Cortex system are located in Denver (Alpine Waste & Recycling) and Minnesota, USA.

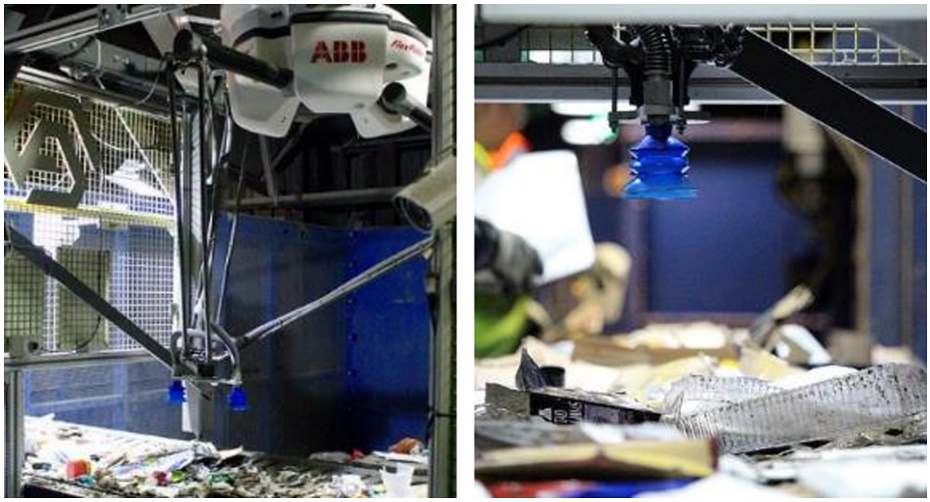

Fig. 10. Cortex sorting system from the company AMP with a suction cup (AMP Robotics, 2019).

3.2.3.6. Sorting systems Bollegraaf. The sorting system RoBB of the Danish company Bollegraaf Recycling Solutions (with Van Dyk Recycling Solutions as a distributor, especially in the USA) was presented at the end of 2013. The system was advertised with the ability to sort different types of plastic and the "paper, cardboard and cardboard packaging"-fraction from mixed waste streams with a fully automatic robot. The system is equipped with NIR sensors and 3D cameras to create a height profile of the waste stream and to identify the individual materials. The sorting takes place via a vacuum gripper, which is mounted as a portal system above a conveyor belt (Van Dyk Recycling Solutions, 2013; Waste Management World, 2013).

Bollegraaf Cogni (see Fig. 11) was presented in May 2018 at the IFAT in Munich (World's Leading Trade Fair for Environmental Technologies). The material is detected using the same technology, but the vacuum gripper is mounted on a delta robot arm for the new model (see Fig. 11, right). According to the manufacturer, the area of application lies in the sorting of various plastics, Tetra Pak, paper, etc. The design makes it possible to integrate this system easily into existing systems since the robot arm is positioned over a conveyor belt (Bollegraaf Recycling Solutions, 2019).

3.2.3.7. Machinex SamurAI. Since 2018, the Canadian manufacturer Machinex has offered a sorting system equipped with Artificial Intelligence from AMP, which can be used for positive and negative sorting as well. The basis of the "SamurAI" system is a delta robot with vacuum gripper (see Fig. 12), which can reach up to 4000 picks per hour. The installed software continuously expands the database in the background with new material data in order to increase the recognition accuracy. The structure of the sorting system is modular, which enables an easy extension of the system if necessary. The maximum object mass, which can be moved through the suction pad, according to the manufacturer is 6 kg.

In addition, customers can use "MACH Vision" (in-house product of manufacturer) to create material identification databases in advance for plant-specific materials, as well as to receive automatic software updates and optimized databases from the same systems in other plants via the "MACH Cloud" (in-house product of manufacturer) installation. Nine plants have already been sold to the US and Canada, where the systems are mainly used to sort plastics (Machinex Industries, 2019).

Fig. 12. Sorting system Machinex SamurAI (Machinex Industries, 2019).

Fig. 11. Bollegraaf Cogni sorting system (Bollegraaf Recycling Solutions, 2019).

3.2.4. Quality assurance

Especially in the field of plastics for recycling and production of Solid Recovered Fuels (SRF) for thermal utilization, the quality of these processed fractions play an important role and is becoming increasingly important. Specifically, quality assurance of Solid Recovered Fuels is currently being done primarily by manual and/or through automated sampling and additionally extensive laboratory analyses. Due to the time-delayed results (sometimes up to several days), there is usually no longer a possibility to influence the quality of the fuels, because they are already produced. Through the application of continuous processes of process analysis or real-time analytics via different sensor technologies (e.g. NIR-sensors), different parameters in the material flow, such as e.g. contained substances, water content, etc. are measured. By linking measured data with substance-group-specific properties stored in databases (e.g. calorific value, chlorine, ash content, etc.) or additional data determined by sensor technologies, fuel-relevant parameters of the waste can be measured in real-time and actively influenced during processing if necessary. Thereby, it is possible to optimise the plant throughput of a production plant or to adapt the produced fuel quality to the qualities required on the market at the time, etc. (Flamme and Krämer, 2015; Aldrian et al., 2016; Krämer, 2017).

3.2.5. Human-Machine-Interface (HMI)

HMI describes computer-assisted user interfaces that enable the user to communicate with a (computer-)program. Especially in the area of robotic technology and Internet of Things in combination with HMI, Gautam et al. (2014), Nuamah and Seong (2017) and Thomessen and Kosicki (2012) published peer-reviewed articles.

3.3. Business models

The development of new business models and the technological advance go hand in hand – new technologies require innovative business models to be able to compete in the market and new business models evolve through technical solutions. Amongst others, companies already work on service solutions for reverse logistics of used parts (e.g. CoremanNet, 2019). Through digitalisation, this solution could spread into other areas of waste management. Over the next few years, the waste management industry is forecasting an innovation leap, especially in the areas of digital platforms/digital communication, "product as a service" and "predictive maintenance".

3.3.1. Digital communication

As mentioned, in waste management digital platforms have (further developed) in recent years to, for example, carry out disposal orders or exchange information between customers, producers and service providers. BauTastisch (2019) offers customers information on the purchase and sale of building materials, tools and construction machinery, while Schrott 24 (2019) provides information on the possibility of selling scrap metal. Amongst others, digital platforms for the online booking of container systems for the disposal of waste have become established on the Austrian and German waste market.

Via the two platforms, WasteBox (2019) and WasteBox Biz (2019) private individuals or construction companies can book waste disposal orders for different types of waste with just a few clicks. The size of the container can be selected and ordered on the homepage. The container is then delivered to the desired location and picked up again if necessary. Additionally, various waste containers can be easily ordered via Container Online (2019) and Containerdienst 24 (2019). Similar to the Austrian companies WasteBox and WasteBox Biz, the companies Redooo (2019) and Remondis (2019) provide the booking of container systems for private and commercial customers in Germany via a digital platform. Also, some oversea companies offer online bookings for disposal solutions (e.g. Rubicon (2019) in the USA respectively Easy Skip Hire (2019) in Australia).

3.3.2. Predictive maintenance

The topic of predictive maintenance describes the ability to predict the remaining service life of machine and plant components through the use of sensors, parameters and data tools. Based on the four pillars of digitalisation – interconnectivity, digital data, automation and direct value creation – optimal maintenance and replacement timings and operating conditions can be identified based on patterns of critical operating parameters. The combination of service and digitalisation offers tremendous potential as a key innovation because a certain part of the total operating costs of machines and plants are caused during service phases. Hence, this topic not only concerns clients but also EPCs (Engineering, Procurement and Construction), machine and plant manufacturers, technology companies, process/measurement/control technicians, etc. Detailed information on the topic of maintenance was published by the Green Tech Cluster (2017a) in the form of a Green Tech Radar.

3.3.3. Product as a service

Product as a service describes a concept where selling pure service or product performance is paramount and selling of actual product moves into the background. This is still not directly relevant for waste management sector but for the benefit of better understanding of possibilities and creation of additional awareness, examples are offered, amongst others, by the following companies and the mentioned services in other sectors:

- Xerox: Leasing of office equipment (Xerox, 2019),
- Rolls Royce: Service agreement "Power by the hour" enables the maintenance and repair of engines with fixed prices per operation hour (Rolls Royce, 2019),
- Philips: The "pay-per-lux" model provides light as a service and costumers pay for the supplied light output (Atlas of the future, 2019),
- Michelin: The tyre manufacturer offers fleet management for tyre service (Michelin, 2019) and
- Hilti: This company provides fleet management for construction machines (Hilti, 2019).

3.4. Data tools

The modelling of processes for waste processing is hampered by the heterogeneity of waste. For this reason, development is moving strongly towards multivariate model equations, Deep Learning and Machine Learning. All these models are based on large amounts of data which can be generated and made accessible in different ways. Gu et al. (2017) and Wen et al. (2018) are engaged in the topic of industry 4.0 and big data in waste management.

3.4.1. Blockchain-Technology

In 2017, blockchain technology became known mainly through the use of cryptocurrency. The technology is by no means limited to this area of application, but can in principle be used wherever secure data storage has to take place without a central instance. In the field of "green technologies", the use of blockchain technology can basically be integrated into the following categories: energy industry, industry & internet of things, smart city and innovation engine, payment systems & fintech. Currently, however, the use of blockchain technology focuses primarily on the financial sector (e.g. Bitcoin). As an example, for the use in the energy sector, a project in New York can be mentioned where electrical energy from photovoltaic systems of residents can be obtained via Blockchain (Siemens, 2018). Experts predict that the technology will also prevail in many other industries and open up new business models (Green Tech Cluster, 2018b; Green Tech Cluster, 2019).

3.4.2. Statistical design of experiments

The statistical design of experiments makes it possible to determine empirical description models for the behaviour of systems with as few attempts as possible. Such models, for example, allow to identify the most important influencing factors, to make predictions about the system behaviour or to determine optimal factor settings. An example of system behaviour hereby can be the power consumption of a machine. Factors are external influencing factors, such as for example, the speed of a drum screen.

In this case, the statistical design of experiments specifies the combinations of factor settings to be investigated for a selected description model so that the system can be described within certain factor limits with minimal effort. Since empirical model equations without theoretical basis are used, the model obtained may, according to Siebertz et al. (2010) only be used for interpolation but not for extrapolation. As an example of such a model, equation formula (1) shows the quadratic description model for n_f factors, where y describes the system behaviour, the values x represent the settings of the factors, and the values c are the model constants.

$$y = c_0 + \sum_{i=1}^{n_f} c_{i,1}x_i + \sum_{i=1}^{n_f} c_{i,2}x_i^2 + \sum_{i=1}^{n_f-1} \sum_{j=i+1}^{n_f} c_{ij}x_ix_j \tag{1}$$

An example for the application of the statistical design of experiments on the description of waste processes is found in Kazemi et al. (2016) where the influence of various factors on the composting of municipal waste in investigated.

3.4.3. Building information modelling (BIM)

BIM technology has become established in many industries in development and production several years ago. In waste management, BIM is mainly used in the construction industry as a data source for raw materials. Hereby, the focus of BIM lies on the consistent use of a digital 3D construction model over its entire life cycle. In the years to come, one can see further development in the four areas of planning, design, component manufacturing and facility management by 2024 (Green Tech Cluster, 2017b). Especially in the field of waste management, Bonifazi et al. (2018), Opelt et al. (2018) and Cheng and Ma (2013) dealt with the topic of BIM and published technical papers. Additionally, the Green Tech Cluster (2017b) became a publisher of an extensive Radar journal on this subject.

3.4.4. Multivariate analysis

The multivariate analysis allows the simultaneous comparison of several (statistical) variables or random variables and is used in multivariate statistics. In engineering, for example, these models are used in the chemometric analysis where the most suitable wavelength can be determined using (NIR) sensors. Increasingly, this method is applied in the configuration of sensor-based sorters or in the development of material-machine-models where optimal operating points can be determined (Green Tech Cluster, 2018a).

3.4.5. Deep Learning

Deep Learning is concerned with a special kind of information processing and uses neuronal nets (nets of artificial neurons) as well as large amounts of data to mimic the learning processes and decision-making processes of the human brain. Thus, machines are enabled to improve their skills without human help. Users have the convenience that systems are provided with data and questions which are independently evaluated. The information obtained this way can be correlated or linked with other data which results in increasingly more connections in the neuronal net that develop in and between single layers. The more neurons or layers the neural network has, or the denser the network becomes, the more complex decisions can be made.

In waste management, Deep Learning processes are for example used in the sensory robotic sorting of construction waste. Hereby, the system is trained with examples of the fractions that need to be sorted out and therefore is able to recognize objects of the same structure.

3.5. Market survey

As already mentioned at the beginning of this paper, in the course of the project *ReWaste4.0* companies from the waste management and disposal sector of the DACH region (Germany, Austria and Switzerland) were interviewed regarding the field of waste management 4.0 via an online questionnaire. The survey focused on the following topics:

- Market needs, trends and requirements for waste management 4.0,
- Digitalisation and networking of waste management and
- Need for governance measures.

From this, nine specific questions were formulated that allow both open and closed answers. When formulating the answer options, care was taken to cover all possible cases and to be as non-overlapping as possible. The reason for the rather small number of questions was, on the one hand, the fact that companies want to invest little time in general surveys and on the other hand, there was a desire to achieve a high response rate. Specifically, the following questions were asked:

- What company size would you associate your company with?
- Which opportunities/risks do you generally see in the topic of "waste management 4.0"?
- Is your company already involved in the digitalisation in waste management?
- If so, in which topics?
- Will you also deal with this topic in the future?
- What expectations do you have for your company after implementing "waste management 4.0"?
- Are you planning concrete investments in the field of "waste management 4.0"?
- Are legal or steering measures currently necessary in the area of "waste management 4.0"?
- What does your company specifically need for the introduction/implementation of "waste management 4.0" projects?

The survey was carried out from August 24, 2017, until January 16, 2018. In this period 1214 companies visited the online questionnaire via the provided link. Of these, 394 fully answered the questionnaire which corresponds to a relative high overall evaluation rate of 32.5%. 18 companies only submitted a partially filled out questionnaire and 801 used the link to the questionnaire but did not fill it out and therefore could not be included in the evaluation.

Basically, by the above-average participation in the survey, it can be stated that the topic of digitalisation in waste management is pressing and that there is great interest from the industry. From the results, it could be ascertained that for the implementation of digitalisation within a company, above all software solutions, qualified employees and/or training offers as well as co-operation with

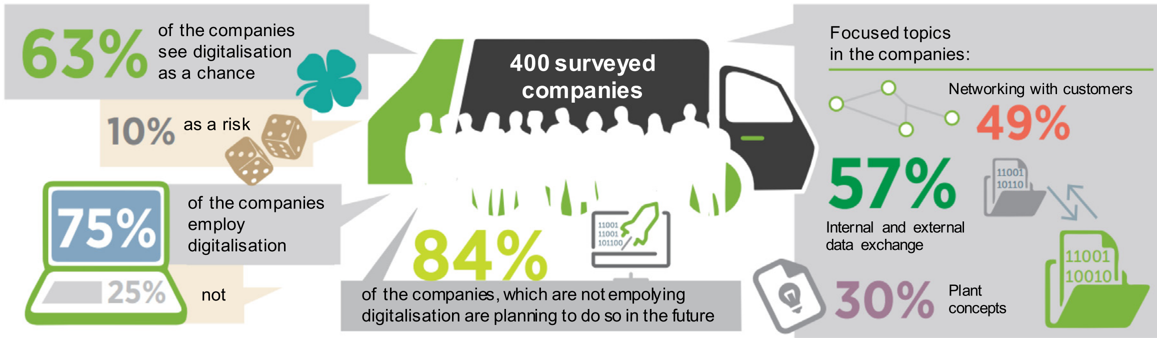

Fig. 13. Summary results of the conducted survey (Green Tech Cluster, 2018a).

the industry are necessary (Sarc and Hermann, 2018). The summary of the results of the survey are strikingly illustrated in Fig. 13.

4. Conclusions

From the presented scientific results and market figures, data, facts and information, it can be seen that, along with other industrial sectors, waste management is also inexorably developing towards digital industrialisation. In order to be able to successfully implement the technologies, it is necessary that the systems adapted to customers are coordinated with industrial companies (recovery industry and their suppliers). On the one hand, the quality requirements of the industry (which, among other things, uses secondary raw materials and energy) are becoming even higher; on the other hand, the requirements are becoming increasingly stringent from the point of view of environmental legislation. In order to deliver the required material qualities, optimisations in logistics and plant concepts are necessary. The methods of digitalisation will make it possible to achieve these improvements. In addition, new business models based on digital technologies will increasingly evolve, contributing to the success of digitalisation along the value chain.

Also, from the relatively large participation of the contacted companies in the survey, it can be seen that the topic of digitalisation in the waste management industry is trending and of great interest. According to their own statements, a large part of the companies is already dealing with this topic or is planning to do so in the near future. Currently, especially different digital solutions such as electronic invoices, service portals for customers, paperless order processing, container tracking, vehicle tracking and tracking for dispatchers or level measurement in waste containers are in use. Often, different solutions for online waste management are already available, as well as various systems for intelligent waste collection.

Summing up, it emerges that intelligent, robotic-based sorting systems in waste management continue to be of increasing interest due, among other things, to the partial replacement of humans or the addition of robots, relieving people of the sometimes heavy physical sorting work and liberating them of a work area with not always optimal environmental for health conditions (noise, dust, dirt, pollutants, etc.). Robots also enable the lifting of heavier objects, which is why pre-shredding gains more importance up to certain sizes. However, there are selected limitations regarding highly efficient application of modern technologies (i.e. in present case robotics technologies) that have to be noted like:

- Material specific limitations: complex material distribution, complex and heterogeneous material types in combination with surface contamination, different particle sizes, shapes and surface structure of particles, as well as
- Technology specific limitations: optimal supply of material flow in machine/plant, detection of material type and position of particle, sensor efficiency (e.g. for detection), particle position changes after detection and prior sorting, actuator (e.g. robot arm) efficiency, actuator limitations in its size, velocity, reaction time and number of picks per hour, etc.

Furthermore, the automated analysis of waste (material detection) has advanced so far thanks to the use of sensors, Artificial Intelligence and access to databases that materials can be captured quickly without any problems.

Basically, digitalisation in waste management is based on macroeconomic growth. Competition is promoted and labour productivity increased, which in principle benefits the consumer. Nevertheless, it is necessary to set steering and regulatory measures such as, for example, the flexibilisation of employment structures and broadband expansion, but at the same time the further development of the legal system (e.g. with regard to data protection) and a further training policy geared to the use of ICT. The changes in the industry associated with digitalisation will also change the labour market, as the technologies have great innovation and growth potential.

To achieve the recycling targets defined by the European Circular Economy Package several actions from the member states are required to optimize the national waste management towards circular economy. To increase the current recycling rates and reach the demanded rates, robotic technology for waste sorting can be implemented for selected waste materials. To apply this technology successfully, additional steps e.g. material detection through sensors, must be taken into consideration, which require datasets with material-specific information and future research in the area of sensor fusion. Compared to other industries, "digitalization" is a new topic in the waste management sector and therefore mayor improvements are possible. This is also visible in the development of the market volume for "green products" and "circular economy": in 2013, the global market volume amounted to 2536 billion euros (€). By 2025, an increase of up to 5385 billion euros (€) is predicted. Of this, around 100 billion euros (€) was spent on the circular economy in 2013. This amount will rise to 170 billion euros (€) by 2025 (Berger and Büchele, 2014).

Declaration of Competing Interest

The authors declare no conflict of interest.

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