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Digitalization of waste management: Insights from German private and public waste management firms

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Abstract

Policymakers, practitioners, and scholars have long-lauded digital technologies, such as smart waste containers or artificial intelligence for material recognition and robotic automation, as key enablers to more effective and efficient waste management. While these advances promise an increasingly digitalized future for collecting, sorting, and recycling waste material, little is known about the current extent of digitalization by waste management firms. Available studies focus on firms' digitalization intentions, largely neglecting the level of actual adoption of digital technologies, and do not differentiate the level of digitalization alongside different steps of the waste management value chain. Our study reports on a cross-sectional descriptive survey that captures current digitalization efforts and strategies of 130 public and private waste management firms in Germany. We analyze their levels of digitalization along with different steps of the waste management value chain, explore their different objectives, approaches, and transformational measures with regard to digitalization. Our findings reveal that while the perceived importance of digitalization in the waste management sector continues to grow, the actual adoption of advanced digital technologies falls notably behind intentions reported in 2016 and 2017. We explore the reasons for this gap, point out so far largely ignored research opportunities, and derive recommendations for waste management firms and associations.

Keywords

Digitalization, digital technologies, waste management, adoption, survey

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Introduction

Waste management has traditionally been a physical and mechanical sector focussing on the collection, sorting, and recycling or incineration of waste material. However, it is increasingly being targeted by solution providers that promise more effective and efficient operations through digital technologies, such as smart bins (e.g. Bigbelly, 2020), on-demand semi-autonomous trucks (e.g. Rubicon, 2020), or artificial intelligence (AI) for material recognition and robotic automation (e.g. AMP Robotics, 2020; ZenRobotics, 2020). In recent years, a number of new methods for waste management have emerged that are embodied in and enabled by digital technologies[1], such as waste treatment on the basis of image recognition and machine data analysis (Waste Management World, 2021) or onsite waste separation through bin-integrated material detection sensors (Green Creative, 2018).

Notwithstanding these innovative use cases, little is known about the waste management sector's current extent of digitalization, that is, the conversion of physical or analog processes, contents, or objects into a digital format by help of digital technologies (Fichman et al., 2014; Fitzgerald et al., 2014). Existing literature on the digitalization of waste management has focused on explorations of *future* digital technologies, such as concepts for digital waste management in sustainable cities (Anagnostopoulos et al., 2017; Esmaeilian et al., 2018), simulations for digital dispatching and routing (Ramos et al., 2018; Shah et al., 2018), smart bin prototypes (Rovetta et al., 2009), or software-enabled image classification for waste sorting (Wagland et al., 2012). Only three quantitative studies exist (Mavropoulos, 2017; Mechsner, 2017; Sarc and Hermann, 2018). However, these studies focus on firms' digitalization *intentions*, largely neglecting the level of *actual adoption* of digital technologies, and do not differentiate levels of digitalization alongside different steps of the waste management value chain, such as between customer management & sales, dispatching & logistics, weighing & sorting, marketing of recyclable materials, recycling, disposal, or container management.

We address these limitations through our study that asks the research question: *"What is the status-quo of digitalization by private and public waste management firms in Germany?"* We report on a cross-sectional, descriptive survey that captures

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current digitalization efforts and strategies of 130 public and private waste management firms in Germany.

Method

Survey design

We conducted a quantitative cross-sectional online survey (Pinsonneault and Kraemer, 1993). The purpose of our survey was description, not explanation or prediction (Malhotra and Grover, 1998). Our aim was to ascertain facts about the status of digitalization such that a systematic basis of empirical data is laid out for future hypothesis development.

To design the survey, we consulted the literature, carried out four practitioner interviews, and visited three waste management firms (Appendix A) to understand the German waste management sector in terms of market structure, industry forces, typical value chain, and digital technologies relevant to the industry. Our unit of analysis were waste management firms (Karanja and Zaveri, 2013). We focused on capturing their current levels of digitalization, across (a) all steps of the waste management value chain, and (b) the variety of currently available digital technologies.

Regarding (a), we differentiated the waste management value chain into four successive and one cross-sectional step (Kerdlap et al., 2019; Sarc et al., 2019). Appendix B summarizes our conceptualization of a waste management value chain.

Regarding (b), we identified relevant digital technologies from prior digitalization studies in waste management (Mechsner, 2017; Sarc and Hermann, 2018) as well as other industrial sectors (Justenhoven et al., 2019; Reker and Böhm, 2013) and from our interviews and observations. Appendix C summarizes the technologies we consider.

Instrument development and testing

We followed the instrument development procedure by Moore and Benbasat (1991). First, we defined key measurement categories on basis of our understanding of the literature, our interviews, and site observations. To ensure comparability to prior waste management digitalization studies we included key measurements from prior studies, such as perceived impact of digitalization (Mechsner, 2017; Sarc and Hermann, 2018). In total, we identified seven measurement categories for our survey:

A) **Firm classification**. We distinguished various waste management roles according to the firms' pursued main value-add activity.
B) **Digitalization of the waste management industry**. We captured the firms' perceived relevance and impact of digitalization to the waste management industry (Mechsner, 2017; Sarc and Hermann, 2018).
C) **Digitalization along the waste management value chain**. For each value chain step, we measured the firms' current implementation status of various digital technologies and their technical interfaces through which data can be exchanged.
D) **Digitalization strategy and objectives**. We captured the firms' strategic digitalization plans according to their transformational responsibilities, objectives, and measures (Salviotti et al., 2019; van Alphen et al., 2019).
E) **Digitalization drivers and barriers**. We identified key external and internal factors that drive or hinder the firms' digitalization measures (Pflaum et al., 2017; Reker and Böhm, 2013).
F) **Digitalization outlook**. We captured the firms' digitalization expectations according to their evaluation of innovative digital technologies and their likely investments (Sarc and Hermann, 2018; van Alphen et al., 2019).
G) **Demographic data** of firms to describe our sampling frame.

Second, in total, we created 61 measurement items (43 nominal, 18 ordinal) across these categories. For attitudinal measurements, we used 5-point scale matrices balancing the scales with an odd number of points and a neutral midpoint (Brace, 2004). For behavioral measurements, we used a 4-point scale with the pre-codes "not relevant," "planned," "in implementation," and "in use." We ensured that the items were mutually exclusive, as exhaustive as possible, and of appropriate detail (Brace, 2004). We incorporated no-response answer options for all questions except for demographics (Dillman, 2000; Ryan and Garland, 1999). All ordinal scales were controlled for order effects (Artingstall, 1977) and acquiescence (Kalton et al., 1980). We rotated some items to prevent bias (Brace, 2004).

Third, we ensured content validity and face validity (Straub, 1989) by conducting an informal survey pilot with eight practitioners from a medium-sized waste management system service provider (Andrews et al., 2003). Based on the feedback, we revised the survey by adjusting the wording of some items and codes that were unclear and adopted the order of some pre-codes to align them with the value chain logic. The final survey questionnaire comprises 65 items (Appendix D).

Participants and procedures

We used non-probabilistic convenience plus unrestricted self-selected sampling (Schonlau et al., 2001; Truell, 2003). First, we contacted 831 private certified German waste management firms specialized in waste collection with the help of a medium-sized system service provider who distributed the link to the online survey by email. Second, to include public waste management firms, public–private partnerships, and non-certified waste management firms, we published a call for survey participation in German waste management trade magazines (*EUWID Recycling und Entsorgung, 320grad.de, Recyclingmagazin, ZfK Zeitschrift für Kommunalwirtschaft, e-mag Entsorgungsmagazin*, and *RecyclingPortal.eu*).

The online survey was live between June 15 and July 3, 2020. We sent two reminders, via post on June 22, 2020 and via email on June 29, 2020. Observing response spikes shortly after these dates, we considered the reminders effective.

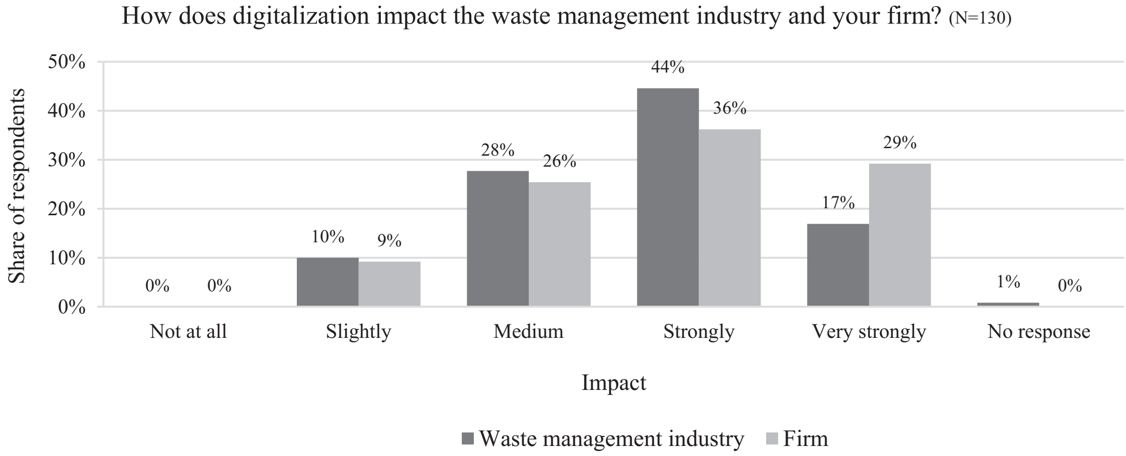

Figure 1. Influence of digitalization on waste management industry and firms.

Data screening, cleansing, and analysis

We received 241 responses. We removed 111 responses from participants who started the questionnaire but did not proceed beyond the first page (94 in total), showed biased response patterns, such as unrealistic survey completion times, extreme tendencies, or systematic answer patterns (5), or did not match our target population (12).

The large majority (91%) of the 130 respondents are commercial waste management firms. Eight municipal waste management firms and four others, such as a public-private partnership, participated in the survey. In total, 120 companies (92%) were certified as specialist waste management firms.

Most respondents (58%) were between 40 and 59 years old. The most often reported positions (28%) were owner, board member, or top manager, followed by other managerial positions (24%). The highest share of respondents (39%) worked for mid-size waste management firms that employ between 50 and 249 employees. Firms with less than ten employees, who make up about 60% of the German waste management sector (Statistisches Bundesamt, 2020), are underrepresented in our study (3%). Contrarily, firms with more than 50 employees are overrepresented in our study.

Before we commenced data analysis, we compared response means for 41 variables between early and late respondents through a Mann-Whitney-U test. Six variables (Management's attitude toward digital change, Relationship between opportunities and risks, Potential impact of digitalization on customer management & sales, Potential impact of digitalization on weighing & sorting, Relevance of online marketplaces for future business model, Sum of the averages of internal drivers) showed a statistically significant difference, with early respondents reporting higher scores on these variables than late respondents. However, since our analysis of our data shows that small firms are on average less digital than larger firms, the difference between early and late respondents may also have emerged from the different distribution regarding the number of employees. We therefore decided to proceed with 130 survey responses in our analysis.

Because our survey's purpose was descriptive, our data analysis strategy primarily relied on identifying relevant summative statistics (such as means, medians, standard deviations) and visualizations (such as box plots, pie charts, bar charts). But where appropriate, we also used inferential statistics to examine the statistical significance of between-group variations and correlations through chi-square, Mann-Whitney-U, and Kruskal-Wallis tests (Tabachnick and Fidell, 2014). We also performed cluster analysis based on the k-means algorithm (Ward method) to identify groups of respondents. We computed these tests using SPSS version 27.

Findings

Perceived relevance of digitalization to waste management

About 60% of all respondents currently perceive a strong or very strong impact of digitalization on their industry and on their firm (Figure 1). Approximately one out of ten respondents perceive only a small impact of digitalization on the industry and the firm. More respondents expressed a very strong influence of digitalization on their firms (29%) than on the industry (17%). Contrary to that, a strong impact of digitalization is indicated more often for the industry (44%) than for the firm (36%).

We statistically explored differences in responses by organizational size. Our data shows that respondents with less than 50 employees feel on average statistically significantly less impacted by digitalization than respondents with more than or equal to 50 employees (Mann-Whitney-U test: $z = -2.197$, $p = 0.028$). Small firms are also statistically significantly more dispersed in their responses than larger firms. While about 20% to 30% of the small waste management firms each indicated a small, medium, strong, and very strong impact of digitalization on their firm, larger firms perceive majorly a strong or very strong impact (71%) (χ^2 [3, n = 99] = 15.482, $p = 0.001$).

We discovered that 30% of the respondents believe that digitalization impacts their own firm more than the industry. 21% indicate that digitalization has a stronger impact on the industry than on their firm, the remaining 49% see an equally strong impact of digitalization on their firm and the industry. The number of employees has no influence on this distribution.

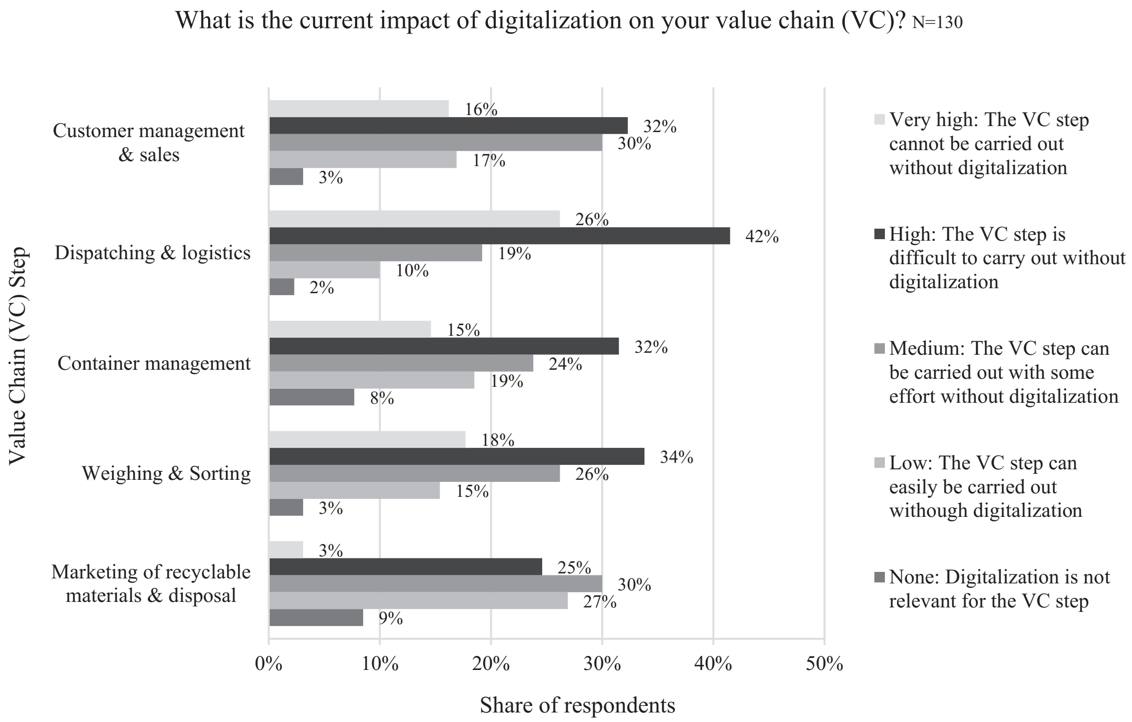

Figure 2. Current impact of digitalization on waste management value chain.

The majority of respondents (66%) view the digital change with confidence and observe either only opportunities or more opportunities than risks (74%). Approximately one quarter of the respondents has a neutral attitude toward the digital change (28%) and observes balanced risks and opportunities (22%). A small minority observes more risks than opportunities (5%) and feels concerned about the change (7%).

Current extent of digitalization in waste management

Digitalization along the waste management value chain. Digitalization has the highest impact on dispatching & logistics followed by weighing & sorting and customer management & sales (Figure 2). Two third of the respondents believe that dispatching & logistics is currently difficult (42%) or even impossible (26%) to be carried out without digitalization. Roughly half of the respondents believe that weighing & sorting and customer management & sales are difficult or impossible to be carried out without digitalization. Marketing of recyclable materials, recycling & disposal was indicated to be less impacted by digitalization. Today, less than 5% assume that this value chain step cannot be carried out without digitalization.

Analyzing the impact of digitalization on the five value chain steps in more detail, we discovered statistically significant differences in responses between commercial and non-commercial waste management firms. Commercial waste management firms feel a stronger current impact of digitalization in customer management & sales (Mann-Whitney-U test: $z=-2.501$, $p=0.012$) and marketing of recyclable materials, recycling & disposal (Mann-Whitney-U test: $z=-1.999$, $p=0.046$) than non-commercial waste management firms.

For **customer management & sales**, our results show that there is not one single channel used by most waste management firms. Customers frequently order by telephone (90%), followed by e-mail (89%), and fax (46%). Of the respondents, 55% use at least one digital sales channel, in particular external online shops (32%), own online shops (31%), and own apps (15%).

Existing internal online shops differ in their degree of functionality. About half of the respondents' online shops offer digital methods of payment (50%) and real-time information on the price (55%). Real-time information on the delivery date and time and automated offer generation are included by one quarter of the online shops. In contrast to those respondents who use the functions, three out of ten respondents do not regard automated offer generation and real-time information on container availability to be relevant.

While almost 60% of the participants use an Enterprise Resource Planning (ERP) system, only 13% of them have it connected to systems of their customers, system service providers, or other waste management firms. This lack of interfaces and standards can also be noticed when examining the familiarity of the respondents with the standard for the exchange of order-related data, AvaL. Only 31% of all respondents have heard about AvaL. Furthermore, only 24% of the respondents use an automatically processing invoice standard such as ZUGFeRD. Instead, 95% of all waste management firms send their invoices via mail. 82% of the participants send invoices by email.

In **dispatching & logistics**, 61% of the participants currently rely on digital technology. Digital dispatching systems are statistically significantly more used by firms with 250–1000 employees (92%) compared to firms with 50–249 employees (75%), more than 1000 employees (59%), or 10–49 employees (38%) (χ^2 [3, n=99]=14.264, $p=0.003$). Next to digital dispatching systems,

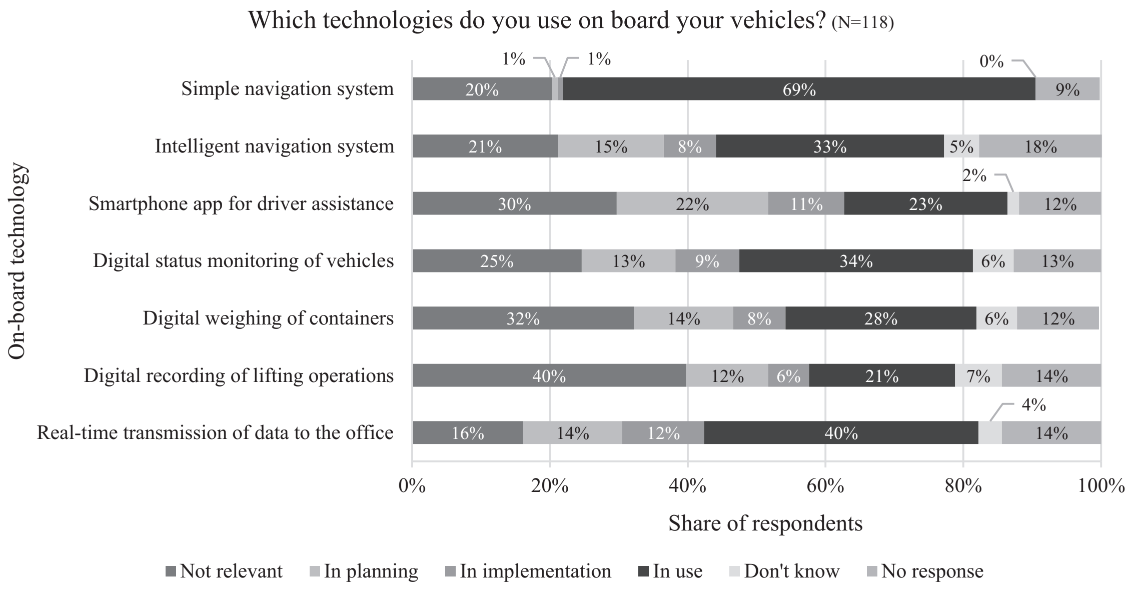

Figure 3. Use of digital technologies on board of vehicles.

waste management firms plan their routes with online maps services (30%), pen and paper/ whiteboard (17%), or spreadsheets (17%). Besides, not all firms who have a digital dispatching system use it for informing their drivers about the dispatching plan (73%). Instead, drivers are often informed personally (50%), by a plan or stack of orders in the office (42%), or the drivers are called and informed about the dispatching plan (30%).

The most frequently used technology on board of vehicles is a simple navigation system (69%) (Figure 3). Other technologies (e.g. smartphone app for driver assistance, digital status monitoring of the vehicles, real-time transmission of data to office) have been implemented by between 21% and 40% of the respondents. In contrast, between 16% and 40% of the participants do not regard these digital technologies to be relevant.

Of all respondents, 68% use a telematics system, of which 69% use it for process optimizations and 17% for control purposes. 73% of the respondents using a telematics system also use a digital dispatching system. Firms that use an ERP system employ a telematics system statistically significantly more often than firms that do not (Mann-Whitney-U test: $z=-2.192$, $p=0.028$).

73% of respondents use a printed proof of performance that needs to be signed with a pen; 35% of respondents use geocodes and time stamps; only 29% store the proof of performance on a digital device where the customer provides a digital signature. Often, more than one kind of documentation of service provision is used.

Almost 90% of all respondents indicate they use digital technologies to perform **container management** (Figure 4). The most common digital technologies comprise integrated near-field communication tags, radio-frequency identification chips, and barcodes. The digital technologies are primarily used for the location tracking of containers and less for the monitoring of containers' filling levels. For storing the data gathered from tracking containers, 47% of all respondents use an ERP system, 25% spreadsheet, and 15% pen and paper.

For **weighing & sorting**, 27% of the respondents have incorporated a scale into their vehicles. With regard to the proof of weight, 51% of the respondents who own a scale record the weighing note digitally and transfer it to their ERP system. 41% use a printed weight receipt. With regard to sorting, 47% of the respondents who have a sorting plant sort the waste automatically, and 38% sort it manually.

We further investigated the number of digital technologies reported as most relevant by the respondents for customer management & sales, dispatching & logistics, and container management (i.e., digital sales channels, ERP, digital dispatching, telematics, onboard driver app, digital container management). The distribution of used digital technologies differs considerably with regard to the number of employees (χ^2 (18, n=99)=37.234, $p=0.005$). While almost 50% of the respondents with 10–49 employees use zero or one digital technology, more than half of the respondents with 250–1000 employees use four or five technologies.

Running a k-means cluster analysis, we could differentiate the respondents based on their use of six digital technologies into three statistically significant ($p=0.000$) groups: (1) analog waste management firms, (2) firms that use "basic" digital technologies, and (3) digital waste management firms (Figure 5). Group 1 (25% of the respondents) does not use any of the digital technologies. Group 2 (52%) implemented digital sales channels, an ERP system, a digital dispatching system, and a telematics system but no onboard computer and no digital container management. Group three (24%) uses on average all six digital technologies.

Digitalization strategy and objectives. Figure 6 describes **strategic objectives** the participants pursued with digitalization. The top-five planned objectives are driven by efficiency and quality gains, comprising faster payment transactions (76%), cost optimization (75%), increased process quality (73%), increased competitiveness (73%), and increased process transparency (67%). Of these top five planned objectives, all but faster payment

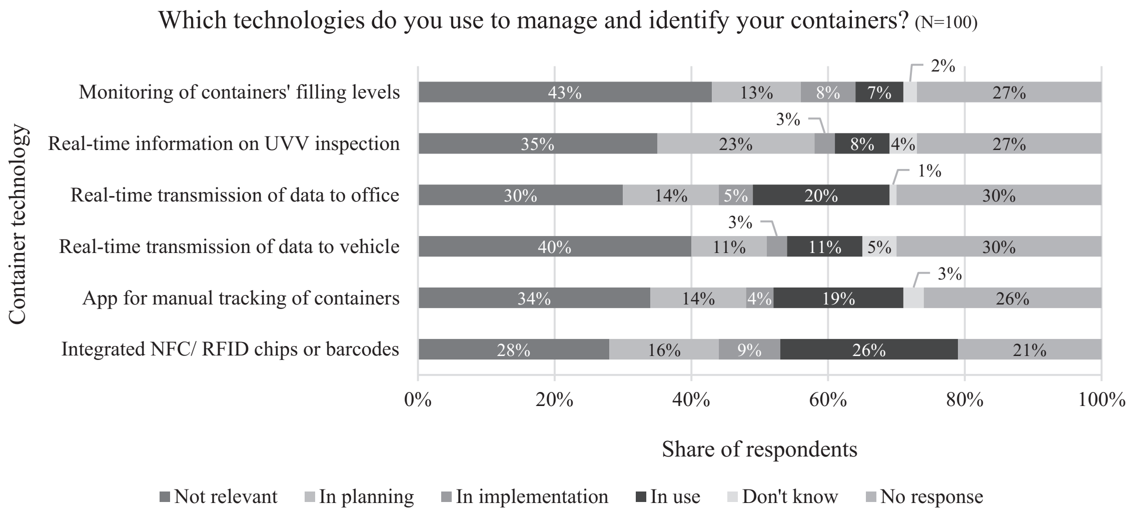

Figure 4. Use of digital technologies to manage and identify containers.
UVV: German accident prevention regulation test.

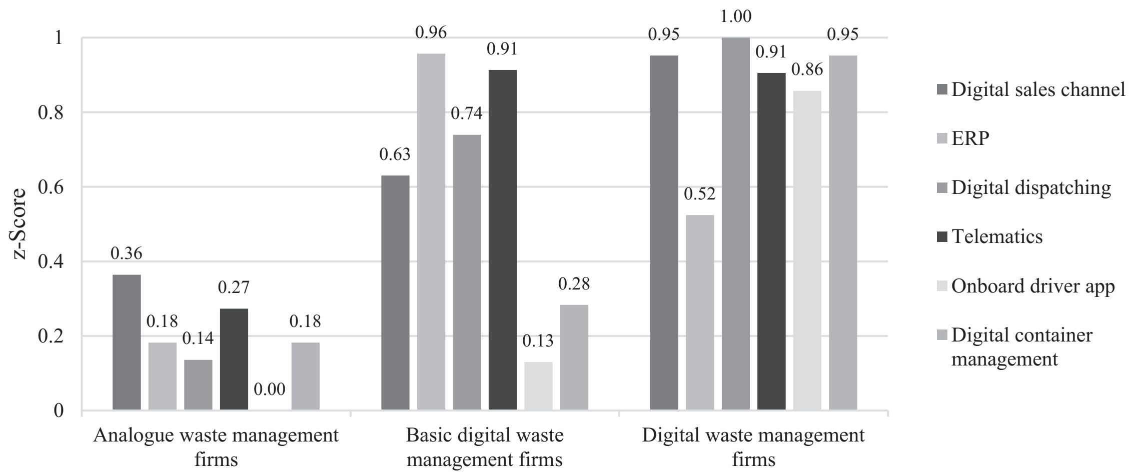

Figure 5. Cluster analysis of current use of digital technologies.

transactions occur in the top-five achieved objectives. Customer experience and expansion are of medium strategic importance pursued through digitalization. Environmental objectives are the least important objectives pursued.

More than half (57%) of survey respondents felt sufficiently or satisfactorily **prepared for digitalization**. One in three respondents (33%) feel well or very well prepared, about one in ten respondents (9%) feels insufficiently prepared. Firm size does not significantly alter the distribution. Yet, the more digital technologies a firm already implemented, the better a respondent feels prepared for digitalization (Kruskal-Wallis test: $H=29.387$, $p=0.000$).

To anchor their digitalization strategies within the firms, the three most preferred **implementation measures** comprise commissioning external service providers (in use: 30%; in implementation: 7%), integrating digitalization into the business strategy (in use: 23%; in implementation 27%), and training employees (in use: 23%; in implementation: 25%). The three least preferred implementation measures comprise cooperating with digital start-ups (not relevant: 52%), establishing a digital business unit (not relevant: 43%), and recruiting new employees with digital expertise (not relevant: 38%).

We found statistically significant differences in the implementation of the measures between firms of different size, except for training employees, which was implemented in all firms. Larger firms significantly more often implement measures to anchor digitalization inside their business (Kruskal-Wallis test: $H=22.829$, $p=0.000$).

Finally, our results show that the **responsibility for digitalization** still resides with the managing director or owner of the waste management firm in the majority of the cases (58%), followed by dedicated IT management roles (37%) and individual department leads (27%). 11% of the respondents indicate digitalization responsibility is entirely missing in their firm.

Digitalization drivers and barriers

Figure 7 displays the top-five **drivers and barriers of digitalization** mentioned by our respondents, distinguishing between internal (I) and external (E) drivers and barriers.

In general, internal factors drive the digitalization of both small and large firms more than external factors. On average, 30% of the

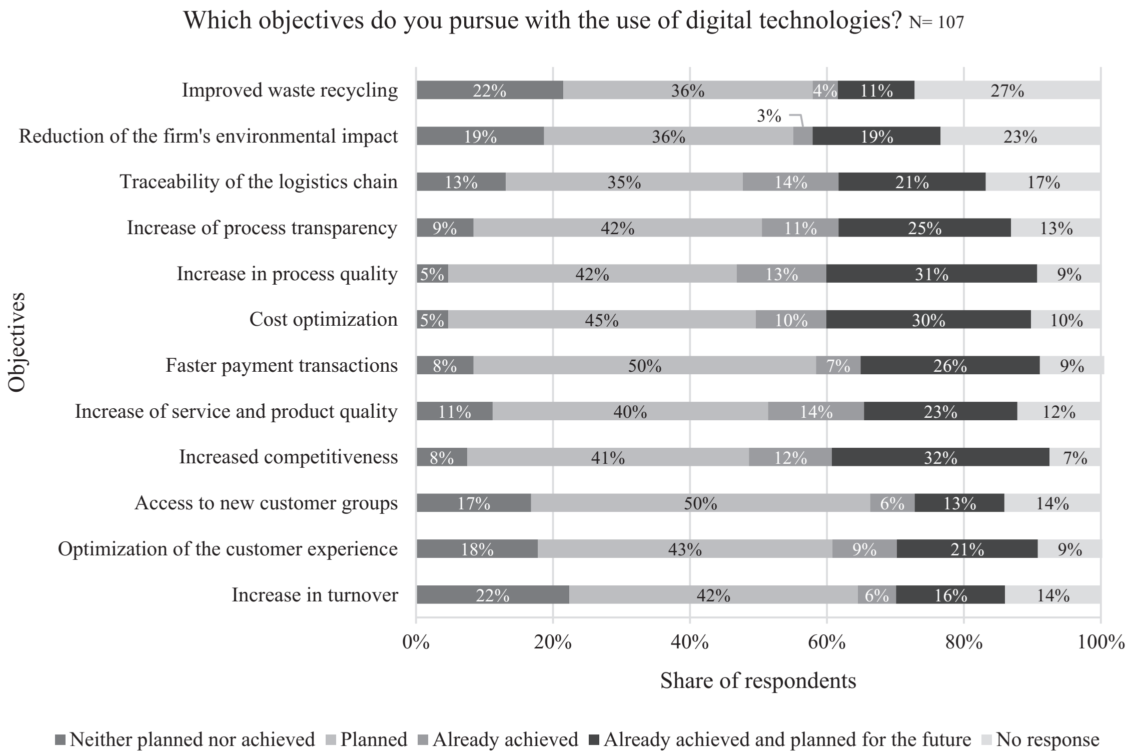

Figure 6. Objectives of digitalization.

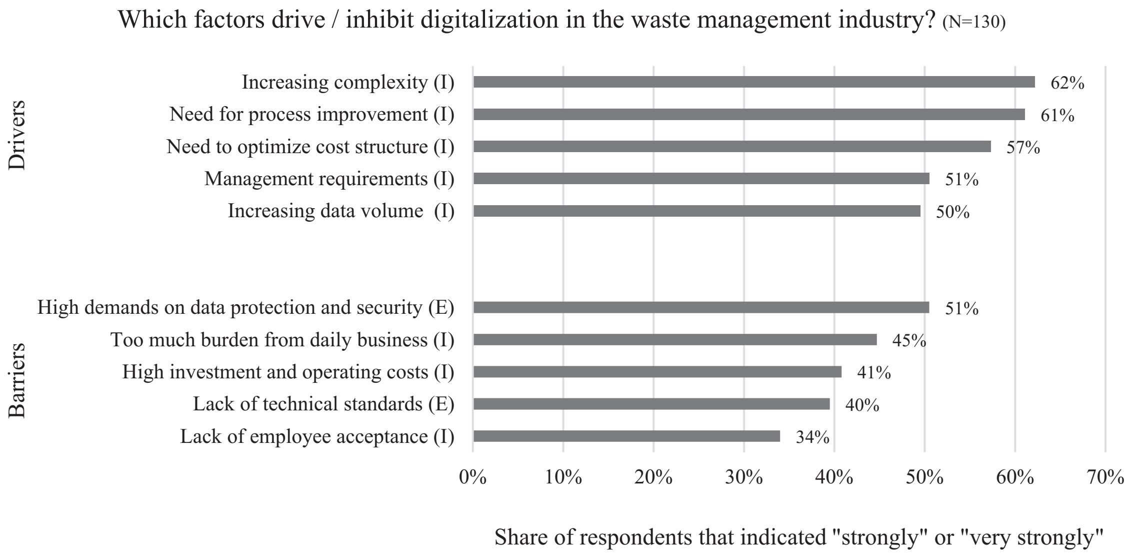

Figure 7. Top five drivers and barriers to digitalization.
I: internal; E: external.

respondents feel strongly or very strongly driven by internal factors, such as an increasing complexity in daily operations, the needs to improve its processes and cost structures, or growing amounts of data that need to be handled. In contrast, respondents specified both internal and external barriers that hinder digitalization. Top barriers concern high demands on data protection and security (strong or very strong: 51%) followed by the burden from operating business (45%) and high investment and operating costs (41%).

Smaller firms feel statistically significantly less driven by internal (Mann-Whitney-U test: z=-2.153, p=0.031) and external factors than bigger firms (Mann-Whitney-U test: z=-2.518, p=0.012). We could not find any statistically significant differences between small and large firms with respect to internal (Mann-Whitney-U test: z=-0.038, p=0.979) and external barriers (Mann-Whitney-U test: z=-0.893, p=0.372) to digitalization.

Besides observing already existent drivers, we asked the participants which conditions would need to be in place to further progress digitalization in their firms. 61% of all respondents state that digital standards would need to be available, 49% see the need for a digital culture and management style, 42% regard the pressure on part of the customers as necessary, and 39% indicate that a pressure on part of the competitors would be required.

Future impact of digitalization on waste management

We examined how survey respondents looked at future digitalization of waste management. Almost 60% of the respondents assume that digitalization will strongly or very strongly change their firm and the industry in the future. 66% of all respondents plan to increasingly deal with digitalization in the future. Notably, our findings show that not all firms who feel a very strong impact of digitalization on their firm and on the industry today also believe that digitalization will very strongly change their industry and firm in the future. 30% of the respondents expect to keep the current level of engagement into digitalization.

Looking into the future, we examined the impact of ten innovative digital technology concepts such as AI or big data analytics on waste management firms. Our frequency analysis revealed that the Internet-of-Things, AI, drones, blockchain, and autonomous driving are not assumed relevant by a large number of respondents. More than 60% consider these technology concepts either not relevant or only relevant in more than 5 years. For the remaining five technology concepts that we investigated (robotics & sensor technology, online marketplaces, predictive analytics, cloud computing, and big data analytics) almost 50% of the respondents consider these technology concepts already relevant or believe that they will become relevant within the next 5 years.

We used a k-means cluster analysis to split the surveyed sample into three statistically significant ($p=0.000$) groups: Group 1 (42% of the respondents), who on average assumes that the five innovative digital technology concepts big data analytics, cloud computing, online marketplaces, predictive analytics, and robotics & sensorics are relevant within the next 12 months; group 2 (32%), who believes that these technologies will be relevant within the next 5 years (cloud computing and online marketplace) or in more than 5 years (big data analytics, predictive analytics, robotics & sensorics); and group 3 (26%) that either do not know these digital technologies (predictive analytics and robotics & sensorics) or believe that they are not relevant (big data analytics, cloud computing, online marketplaces).

The respondents in group 1 are more aware and informed about digitalization projects in the industry, such as the development of AvaL. 64% of the firms in group 1 have heard about AvaL in comparison to those in group 2 (21%) and group 3 (15%) (Kruskal-Wallis test: $H=9.639$, $p=0.008$).

Discussion

Contributions in comparison to prior studies

Our study complements and expands three comparable prior studies on digitalization of the waste management industry (Mavropoulos, 2017; Mechsner, 2017; Sarc and Hermann, 2018). Our findings suggest a growing **importance of digitalization** in waste management. In 2020, more waste management firms feel stronger impacted by digitalization than 3.5 years ago (+6.5%), more firms perceive opportunities from digitalization than 2 years ago (+10.7%), and more firms report to actively engage with digitalization than 2 years ago (+7.5%).

In terms of implemented **digital technologies**, our findings reveal notable gaps between intentions reported in 2016/17 and today's reality. For instance, while implementation levels of electronic invoicing and digital order processing exceed or almost meet 2016/17 intentions, additional digital customer services, such as live order tracking, are only implemented by 8% of the respondents in 2020 (−42%). Similarly, while our findings confirm advanced implementation levels of disposition and telematics systems, only 40% of the respondents use their telematics system for live vehicle tracking (−25%). Finally, today's implementation levels of digital container identification (55%) do almost meet the intentions from 2016/17 (−5%), but only 7% of our surveyed respondents report an implementation of digital container tracking (-43%).

Our analysis of **digitalization objectives** confirms and expands Sarc and Hermann (2018) who report that in 2017 the three most frequently expected results through digitalization were increased process transparency, increased efficiency, and improved quality. Our findings confirm that waste management firms continue to pursue a cost leadership strategy (Porter, 1998) where digitalization objectives focus on the efficiency optimization of internal processes. Such objectives manifest in a limited set of implemented digital technologies with more advanced digital technologies (e.g. sensor-driven live order tracking) remaining irrelevant for achieving cost leadership. This is also reflected in our list of neither planned nor achieved digitalization objectives revealing that environmental optimization and customer-related optimization are largely ignored by waste management firms today.

Three of the top four **barriers** reported in 2016/17 (Mechsner, 2017) still hinder the implementation of digital technologies today: daily business burden, high investment and operating cost, and missing technical standards. While in 2020 high demands on data protection and security has been reported as key barrier to digitalization, it was not reported in 2016/17 at all. This development might be explained through the introduction of the General Data Protection Regulation (European Parliament, 2016) that in Germany became enforceable in May 2018 and, since then, has been lauded a common digitalization barrier in various industries (Dehmel and Kelber, 2020). While digital standards remain the top prerequisite for further digitalization, respondents add "softer" factors, such as digital culture & management style, pressure from customer requirements, or pressure from competitors to the list. These "soft" factors—in particular digital culture & management style—are new to the scientific discourse on digitalization of waste management; yet, they confirm latest industry insights that already highlight the role of leadership in the sector's digital transformation (AMCS, 2018).

Implications

Our findings suggest that waste management firms do not fully exploit the potential benefits of digital technologies available today. These findings lead to two main implications. First, because waste management firms implement digital technologies not to substitute but rather complement existing analog solutions, they need to manage both physical and digital processes, which we call *the burden of parallel worlds*. Second, waste management firms predominantly use digital technologies to reduce costs of operations, which is a risky strategy considering the changing business landscape as well as regulatory and societal requirements for waste management practices. We label this challenge *the efficiency optimization limit of digitalization*.

The burden of parallel worlds. When implemented, digital technologies are often used not exclusively for, but rather in addition to, analog tools or processes. For instance, digital sales channels are often used in parallel with traditional, analog sales channels. While 55% of the respondents employ at least one online sales channel, only 3% of them use it in an exclusive manner. Further, only 19% of the respondents who document their provided service via geocodes and time stamps use them exclusively, while almost 75% report that the delivery note is still signed by pen and paper.

Either waste management firms see no need to abolish analog processes because they are part of a well-functioning system or the installed customer base inhibits the exclusive use of digital technologies through existing analog path dependencies. First, the waste management sector can be understood as the epitome of an old, well-functioning system, in which, for instance, the three types of vehicles and containers have not changed over the past 60 years. Further, since the adoption of the first recycling and waste management act in 1996, the fundamental regulatory framework of the German waste management sector has not changed, effectively shielding public waste management firms against private competitors. This history has created a culture of inertia and reluctance to change impeding potentially disruptive digitalization.

Second, customers often demand analog processes, such as a proof of service provision by pen and paper, even though they can also be provided with geocodes and time stamps. As long as customers do not accept or demand a digital service provision, waste management firms are not willing to implement, let alone exclusively use, digital technologies. This “network effect” is particularly detrimental for the adoption of digital standards, such as AvaL or ZUGFeRD, in which a one-sided adoption means failure of the standard essentially impeding an advanced digitalization of customer-related interfaces.

We argue, this non-exclusive adoption of digital technologies risks the unfolding of parallel worlds that impose unnecessary burden on waste management firms. With parallel worlds, waste management firms must not only manage the infrastructure for analog processes but also deal with the operation of less familiar digital infrastructure. Further, both worlds still exhibit touch points, which are more commonly known as “media breaks.” For instance, if orders arrive via telephone, an additional step is required where the analog information is digitally recorded in the system, which is prone to potential flaws arising from manual recording (e.g. typos or process delays). Lastly, the burden of parallel worlds risks negative feedback loops, where negative experiences from non-exclusionary adopted digital technologies affect decisions on future digital technologies hampering an ongoing digitalization of the waste management firm.

The efficiency optimization limits of digitalization. Our survey showed that efficiency optimization is the main digitalization driver at present and in the future. Different explanations for this focus on digitalization as an efficiency driver exist. First, waste management firms may not be sufficiently informed about the potential functionality of digital technologies. For instance, only 31% of the respondents have heard about the availability of order-related data exchange standards. Second, perceived barriers, such as high data protection requirements (51%) and the lack of industry standards (41%), may impede the full exploitation of digital solution benefits. Third, waste management firms might see no need to innovate their processes by exploiting more potentials of digitalization. Waste management firms may simply not be incentivized to exploit the full functionality of their online shops or provide customers with live information on the delivery time of their containers.

By focussing on efficiency optimization, however, waste management firms may overlook the optimization limits of digitalization running the risk of pursuing objectives, which in the mid to long-term do not live up to increasing regulatory, societal, and economic requirements. We are not the first to point out this risk; it was also flagged by Mavropoulos and Nilsen (2020) who call for a disruption of “business as usual” optimizations. Three points about such a change appear worth highlighting:

1. Waste management firms have been traditionally understood as economic actors that efficiently take care of the waste of others. Changing regulations (e.g. extended producer responsibility) as well as large-scale societal trends calling for more sustainable production and consumption practices (Vergragt et al., 2014), impose new, more challenging roles on waste management. It remains questionable that digitalization employed as a cost efficiency driver will suffice to meet these growing requirements.
2. Digital-first waste management start-ups (e.g. Rubicon, 2020) occur on the horizon. While incumbent waste management firms feel safeguarded by high regulatory and economic barriers to entry, the digital promises by start-ups influence the perception of waste producers and policymakers raising the expectations about digitalized waste management.
3. Commercial waste producers start integrating disposal and recycling processes into their own business. This reduces demand for incumbent waste management firms and creates new competitive pressures.

Limitations and future research opportunities

Several limitations need to be mentioned. First, we used a nonprobability convenience sampling approach and distributed the questionnaire via the network of the system service provider resulting in a sample primarily representing private waste management firms with more than or equal to ten employees. Our second sampling technique, the unrestricted self-sampling approach, bears the limitation that the survey needed to be openly accessible. We justify this limitation by the fact that we wanted to open our survey to waste management firms other than those in the network of the system service provider.

Second, our findings are limited to the German waste management sector. It would be interesting to investigate, however, how waste management firms from other regions answer our survey.

Third, future research should expand the temporal reach of our study. Our openly available survey instrument (Appendix D) could be used to build a digitalization progress indicator tool that measures progress in the actual digital transformation of the global waste management industry over time, if a survey such as ours were to be repeated in regular time intervals (e.g. annually).

Fourth, data collection was impeded by the concurrent onset of the Covid-19 pandemic in Europe. While our invitations to participate were distributed digitally and via mail, the onset of the pandemic may have contributed to a perceived lack of time or lack of current relevance.

Fifth, our study did not address the entire waste life cycle. Digital technologies increasingly also feature in new solutions for waste reduction and recycling. For example, image recognition and machine data analysis technologies are being explored to improve waste treatment (Waste Management World, 2021). Future research should therefore expand the topical coverage of our survey to study the progress of digitalization not only in waste management but also waste reduction and recycling.

Conclusions and recommendations

Our findings show that digitalization is an increasingly important topic on the agenda of waste management firms. Yet, many firms only half-heartedly engage with digitalization resulting in nonexclusive implementations of digital technologies that predominantly aim at the optimization of existing, intra-organizational business processes for efficiency.

Our findings confirm the need for further research on the digital transformation of incumbent, largely non-digital infrastructures for waste management. Findings from other domains suggest that network effects may play a significant role in the adoption of digital technologies in incumbent infrastructures with multiple actors (Constantinides et al., 2018). It remains to be investigated whether digital technologies will contribute to a platformization of such infrastructures and whether these technologies will change traditional underlying market and governance structures.

Our findings indicate a gap between reported digitalization intentions and actual adoption for advanced digital technologies. Our insights imply that waste management firms may find that the burden of their operative business and high adoption costs are hindering them in pursuing more ambitious digitalization objectives. As a possible lightweight mitigation strategy, we suggest training existing employees and let them engage with digital technology providers, who offer modular solutions that can be quickly ramped up and tested without large financial and operational risks.

Further, advanced digital technologies tend to exhibit increasing returns to adoption (Fichman and Kemerer, 1999), that is, their benefits grow with more users adopting the digital technology (Katz and Shapiro, 1986). We, therefore, recommend digital technology providers to either employ platform rather than product-centric business models or, at least, ensure that their digital product complies with industry-wide data standards. A platform business logic stresses that digital technology providers are not only selling a digital solution to a waste management firm but essentially to its customers (waste producers) and business partners (waste recyclers) as well. Established data standards ensure that data can flow with the waste stream through the entire waste management value chain, thereby, enabling its end-to-end digitalization.

Our findings also highlight an obligation for waste management associations to continue investing into educating waste management firms about the benefits, barriers, and approaches to digital technologies, and extend these efforts to waste producers as they play an important role in adopting digital technologies as well. New education is required on emergent data protection concerns that hinder many waste management firms in pursuing more ambitious digitalization objectives.

Lastly, we suggest facilitating the exchange between waste management firms and digital start-ups. While digital start-ups were framed as “not very threatening disruptors in the rear-view mirror” in practitioner interviews, we suggest considering them at least as digitalization drivers, valuable informants, and potential technology providers.

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Note

1. See Sarc et al. (2019) for a comprehensive overview of innovative digital solutions for waste management.

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Appendix

Appendix A. Data sources used for contextual immersion, survey development, and validation.

	Source type	Sources	Intention for using source
Primary sources	Interviews	Four interviews (IP1, IP2, IP3, IP4) with employees at a German waste management systems provider One interview (IP5) with a digital officer at a large waste management firm (>1000 employees) One interview (IP6) with the Head of Business Unit Products and Equipment & Business Unit Waste and Packaging of a waste management technology provider	Understand the waste management market structure and VC Get an impression of the status quo of digitalization Validation and discussion of survey findings
	Observations	Three observations (O1, O2, O3) based on visits of German waste management firms	Get to know the processes and activities of a private German waste management firm Get an impression of the status quo of digitalization Examine the firms' attitudes toward digitalization
Secondary sources	Digitalization surveys on the German waste management industry	Lacher and Ziss (2019), Mechsner (2017)	Uncover the status quo of digitalization Identify discrepancies and research gaps Adopt items
	Digitalization surveys on international waste management	Mavropoulos (2017), Sarc and Hermann (2018)	Recognize areas of digitalization that have not yet been studied in the German waste management industry
	Academic papers on digital technologies and solutions in waste management	Anagnostopoulos et al. (2017), Bakici et al. (2013), Esmaeilian et al. (2018), Faccio et al. (2011), Johansson (2006), Ramos et al. (2018), Sarc et al. (2019)	Understand and get to know digital technologies and digital solutions in waste management Gain insights into how digital solutions and technologies can change the traditional VC
	Digitalization studies on other industries	Berger and Volkmar (2020), Deutsche Telekom AG (2018, 2019), Justenhoven et al. (2019), Kersten et al. (2017), Pflaum et al. (2017), Reker and Böhm (2013), Saam et al. (2016), Salviotti et al. (2019), Schäfer et al. (2017), Schug et al. (2007), techconsult GmbH (2020a, 2020b, 2020c, 2020d)	Observe the structure of other digitalization studies Become aware about aspects of digitalization that were neither included in the study on the German waste management industry nor on the international waste management Adopt items and scales

Appendix B. Waste management value chain.

Value chain step	Description
Customer management & sales	Waste producers approach the waste management firm to order a container. Typically, the waste management firm documents and confirms the order, issues a delivery of an empty container, and performs invoicing after waste has been collected.
Dispatching & logistics	Waste containers are picked up—either regularly on a predetermined collection day or on customer demand. A dispatcher of the waste management firm plans when and on which tour the container is collected and informs the drivers. Tour routes are either planned by the drivers themselves or a dedicated dispatcher. On collection, a delivery note is handed out to and signed by the customer.
Weighing & sorting	Collected waste is weighed and sorted into recyclable and non-recyclable waste. If the waste management firm owns a scale, the weight can be determined at the firm's site. Otherwise, the driver uses the weighing services of a third-party provider. Subsequently, the full container is treated on-site or by a third-party waste treatment firm. Sorting is often done by hand and mechanically relying on wind sifting or magnetic separation.
Marketing of recyclable materials, recycling, or disposal	The waste management firm decides on where to channel the collected, weighed, and sorted waste. The firm can either sell recyclable waste to material recovery (i.e. recycling) firms, sell non-recyclable waste to incineration plants, or dispose of waste via dumpsites or export.
Container management	Represents the spatial and temporal coordination and maintenance of waste containers. Central to this step is knowledge about the number of containers and their current location as well as their condition. Container management is cross-sectional, because it connects to the sequential value chain steps described above at various points of the value chain, for instance when deploying or collecting containers at customer sites.

Appendix C. List of digital technologies considered in the survey.

Value chain step	Digital technologies	Description	Reference
Customer management & sales	Online customer portal	The online customer portal represents the point of contact to the customer. Here, customers can for example, order containers, receive invoices, access the status of their orders, make reclamations and get information on their waste.	Piel et al. (2018)
	Enterprise resource planning (ERP) system	An ERP system integrates back-office functions (e.g. sales, procurement, asset management, finance, etc.) into a standard IT application platform with a uniform database.	Weill and Vitale (2002)
	AvaL (data standard)	AvaL is an open standard for the exchange of order-related data between waste management firms, their customers, authorities and other partners. It aims to simplify the communication across firms through a uniform language.	BDE (2020)
	ZUGFeRD (data standard)	ZUGFeRD is a hybrid cross-sector data format for the exchange of electronic invoice data. It integrates structured invoice data in XML format into a PDF document. This enables electronic processing of invoices.	AWV (2020)
Dispatching & logistics	Dispatching system	A digital dispatching system carries out order scheduling, the personnel allocation, and route planning.	IP2, IP3, IP4
	Telematics system	A telematics system enables the transmission of vehicle-related data to the back-office and customer. The scope of application reaches from driver assistance, vehicle tracking, transition of position data, to automatic storage of arrival and departure times.	Osińska and Zalewski (2020)
Dispatching & logistics, Container management, Weighing	Onboard computer	The onboard computer is the central processing unit in the vehicle that supports the driver at every step of the waste collection. Over the touchscreen, drivers access functions such as orders, navigation, maps, container management, scale, camera, transponders or eANV. The onboard computer stores information such as the weight or digital signatures and transfers them on to the back-office.	Piel et al. (2018)
Weighing & sorting	Robotics	"Robotic waste sorting systems are autonomous, multitasking, learning and scalable systems [. . .] [,] capable to separate specific materials"	Mavropoulos (2017: 36)
	Digital watermarks	A digital watermark is an optical code applied on an item. If read by sorting systems, it informs about sorting ways.	de Belder (2019)
Container management	Barcode	"Barcode is an electronic data interchange medium that contains machine readable dichromatic mark that encodes information for objects labeling using an arrangement of geometric symbols"	Hannan et al. (2015: 514)
	Radio Frequency Identification (RFID)	RFID is a data collection technology "used for the identification or tracking of objects or assets and people. The most usual method [. . .] involves storing a specific serial number [. . .] and other information on an RFID tag. An RFID reader can scan and read the tag", convert radio waves into digital information that is then shared with computers, for example, onboard computers to process the data.	Hannan et al. (2015: 515)
Container management, Dispatching & logistics	Sensor	"A sensor is a device that perceives and measures real-world features, such as physical quantities [. . .], and converts them into signals that can be directly observed or adopted by another device"	Hannan et al. (2015: 516)

Appendix D. Survey instrument.

Code	Item	Reference
Classification		
A1	How would you describe the **activity** of your company? (multiple answers possible)	Practitioner interviews
A2	Are you certified as a specialist disposal company according to **EfbV**?	Practitioner interviews
Digitalization of the waste management industry		
DE1	How strongly does the subject of **digitalization** influence the **waste management industry** in general and **your company** in particular?	Justenhoven et al. (2019), Mechsner (2017), Studer et al. (2019)
DE2	How would you describe your company's **approach to digitalization**?	techconsult GmbH (2020b)
DE3	How does the management of your **firm feel about digitalization**?	van Alphen et al. (2019)
DE4	How do you assess the relationship between **opportunities and risks** of digitalization for your company?	Kersten et al. (2017)
DE5	What is the current **significance** of **digitalization** in the various areas of your **value chain**?	Practitioner interviews
DE6	What is the potential **significance** of **digitalization** in the various areas of your **value chain**?	Practitioner interviews
Actual use of digital technologies along the value chain: customer management & sales		
WKB1	Through which **sales channels** does your customer order from you?	Justenhoven et al. (2019), Practitioner interviews
WKB2+ WKB3	Does your **online shop** have one or more of the following **functions**? Follow-up: Please name **other functions** that your **online shop** has that have not yet been queried.	techconsult GmbH (2020d), Practitioner interviews
WKB4	Which of the following e**xternal online shops** do you know?	Practitioner interviews
WKB5	Which of the following **external online shops** do you use?	Practitioner interviews
WKA1	Do you use an Enterprise Resource Planning (**ERP**) system (e.g. SAP)?	Reker and Böhm (2013), Practitioner interviews
WKA2	Is your **ERP system connected** to that of your customers, system service providers or other waste management companies?	Practitioner interviews
WKA3	The **BDE** Federation of the German Waste, Water and Raw Materials Management Industry e.V. is currently developing a standard for the electronic exchange of order-related data (**AvaL**). Have you already heard of it?	Practitioner interviews
WKA4	Are you willing to use the standard?	Practitioner interviews
WKA5	Why are you not willing to use the standard?	Practitioner interviews
WKA6	How do your customers receive their **invoice**?	Practitioner interviews
WKA7	Do you use an automatically processing invoice format, such as ZUGFeRD?	Practitioner interviews
WKK1+ WKK2	Do you notice a **change in customer requirements** in the following areas? Follow-up: Please name **other customer requirements** that you perceive and that have not yet been queried.	Practitioner interviews
Actual use of digital technologies along the value chain: dispatching & logistics		
WDL1	How do you **plan** the **routes** of your vehicles?	Practitioner interviews, onsite visits
WDL2	How do you **inform** your drivers about the **dispatching plan**?	Practitioner interviews, onsite visits
WDL3+ WDL4	Which of the following **technologies** do you use **on board** your vehicles? Follow-up: Please name **other technologies** that you use **on board** of your vehicles that have not yet been queried.	Practitioner interviews
WDL5	Do you have a telematics system?	Practitioner interviews, onsite visits
WDL6	What is the **main reason** for using a **telematics system** in your company?	Practitioner interviews, onsite visits
WDL7	How do you **document the service** you provide to the customer?	Practitioner interviews
Actual use of digital technologies along the value chain: container management		
WKBV1	How to identify and manage your containers?	Practitioner interviews, onsite visits
WKBV2+ WKBV3	Which of the following **technologies** do you use to manage and identify your **containers**? Follow-up: Please name **other technologies** that you use to **manage** your **containers** that have not yet been queried.	Practitioner interviews, onsite visits

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Appendix D. (Continued)

Code	Item	Reference
Actual use of digital technologies along the value chain: weighing & sorting		
WKW1	Do you own a **scale**?	Practitioner interviews
WKW2	What kind of **proof of the weight** do you use?	Practitioner interviews
WKS1	Do you own a **sorting plant**?	Practitioner interviews, onsite visits
WKS2	How do you sort your waste?	Schug et al. (2007), onsite visits
WKS3	What chances do you see in a further digitalization of your sorting plant?	Practitioner interviews
Digital technologies along the value chain: actual interfaces		
WKV1	Which of the following value chain steps is your **ERP system linked** to?	Practitioner interviews
WKV2	Which of the following value chain steps is your **digital dispatching system linked** to?	Practitioner interviews
WKV3	Which of the following value chain steps is your **telematics system linked** to?	Practitioner interviews
Digitalization strategy and objectives		
SZ1	Based on your company's previous activities, how well is your company prepared for digitalization?	van Alphen et al. (2019)
SZ2+ SZ3	What **measures** do you implement to **anchor digitalization** in your company? Follow-up: Please name **other measures** that you are implementing to anchor digitalization in your company that have not yet been queried.	Salviotti et al. (2019), van Alphen et al. (2019)
SZ4	Who in your company is responsible for digitalization?	Vogl (2020)
SZ5+ SZ6	Which of the following **objectives** have you been able to achieve through the use of digital technologies or which of them do you aim to achieve in the future through the use of digital technologies? Follow-up: Please name **previously unasked-for objectives** that you have been able to achieve or are striving for through the use of digital technologies.	Berger and Volkmar (2020), Deutsche Telekom AG (2018), Saam et al. (2016), Sarc and Hermann (2018), Studer et al. (2019), Practitioner interviews
Drivers and barriers to digitalization		
TH1+ TH2	Which of the following **external factors** are currently **driving** digitalization in the waste management industry? Follow-up: Please name **other external factors** that have not yet been queried and that are currently **driving** digitalization in the waste management industry.	Pflaum et al. (2017), Reker and Böhm (2013), Saam et al. (2016), van Alphen et al. (2019), Practitioner interviews
TH3+ TH4	Which of the following **internal factors** are currently **driving** digitalization in the waste management industry? Follow-up: Please name **other internal factors** that have not yet been queried and that are currently **driving** digitalization in the waste management industry.	Reker and Böhm (2013), Practitioner interviews
TH5+ TH6	Which of the following **external factors** currently **inhibit** digitalization in the waste management industry? Follow-up: Please name **other external factors**, which have not been queried so far, which currently **inhibit** digitalization in the waste management industry.	Berger and Volkmar (2020), Justenhoven et al. (2019), Mechsner (2017), Saam et al. (2016), Sarc and Hermann (2018)
TH7+ TH8	Which of the following **internal factors** currently **inhibit** digitalization in the waste management industry? Follow-up: Please name **other internal factors**, which have not been queried so far, which currently **inhibit** digitalization in the waste management industry.	Berger and Volkmar (2020), Deutsche Telekom AG (2019), Justenhoven et al. (2019), Mechsner (2017), Saam et al. (2016), Sarc and Hermann (2018), Schäfer et al. (2017), Studer et al. (2019)
TH9	Which conditions would have to be in place to ensure that the **digitalization** of your business continues to progress?	Saam et al. (2016), Practitioner interviews
Outlook		
AB1	How will the **waste management industry** in general and **your company** in particular **change** in the future due to digitalization?	van Alphen et al. (2019)
AB2	Will you **deal with the digitalization** of the waste management industry in the **future**?	Sarc and Hermann (2018)

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Appendix D. (Continued)

Code	Item	Reference
AB3+ AB4	What **concrete investments** in one or more of the following digital solutions are you planning in the future? Follow-up: Please name **other digital solutions** you have not yet queried, in which you plan to invest in the next 12 months or in the next 5 years.	Practitioner interviews
AB5	How has **COVID-19** influenced your investment planning?	Practitioner interviews, Review rounds with research team
AB6	Which of the following **innovative technology concepts** will have an impact on your **business model** in the future?	Justenhoven et al. (2019), Mavropoulos (2017), Sarc and Hermann (2018)
Demographic data		
PD1	To which **gender** do you assign yourself?	Brace (2004)
PD2	To which **age group** do you belong?	Brace (2004)
PD3	How many **employees** does your company have in Germany?	techconsult GmbH (2020c)
PD4	Which **position** do you have in your company?	Studer et al. (2019), techconsult GmbH (2020a)