Review

The “ReWaste4.0” Project—A Review

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Abstract: ReWaste4.0 is an innovative and cooperative K-Project in the period 2017–2021. Through ReWaste4.0 the transformation of the non-hazardous mixed municipal and commercial waste treatment industry towards a circular economy has started by investigating and applying the new approaches of the Industry 4.0. Vision of the ReWaste4.0 is, among others, the development of treatment plants for non-hazardous waste into a “Smart Waste Factory” in which a digital communication and interconnection between material quality and machine as well as plant performance is reached. After four years of research and development, various results have been gained and the present review article summarizes, links and discuss the outputs (especially from peer-reviewed papers) of seven sub-projects, in total, within the K-project and discusses the main findings and their relevance and importance for further development of the waste treatment sector. Results are allocated into three areas, namely: contaminants in mixed waste and technical possibilities for their reduction as well as removal; secondary raw and energy materials in mixed waste and digitalization in waste characterization and treatment processes for mixed waste. The research conducted in ReWaste4.0 will be continued in ReWaste F for further development towards a particle-, sensor- and data-based circular economy in the period 2021–2025.

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Keywords: mixed waste; municipal waste; commercial waste; waste treatment; recycling; recovery; contaminants; plastics; digitalisation; smart waste factory

1. Introduction

ReWaste4.0 is a long-term oriented, innovative as well as cooperative K-Project (note: the Competence Centres for Excellent Technologies (COMET) programme is a national funding line of the Austrian Research Promotion Agency (FFG) that aims to carry out high-quality research in science–industry collaboration [1]) at the highest scientific, technical and economic level with two partners from science and eight from industry each. The overall innovative objective for the first time is to investigate and partially implement the new approaches of the “Industry 4.0” (i.e., digital networking, communication between waste quality and plant performance, dynamic process control and optimization and others). This innovative development of waste treatment of non-hazardous mixed waste will transform the branch towards a circular economy and enable high-quality recycling and recovery processes. Through ReWaste4.0 the experimental data-based development of waste treatment plants into the so-called “smart waste factory” will be supported. At a material level, the focus is set on the treatment of non-hazardous mixed waste (i.e., mixed municipal and mixed commercial waste as well as selected non-hazardous mixed fractions declared as the “output” of mechanical treatment processes like Solid Recovered Fuels (SRF) that are utilized in cement industry). ReWaste4.0 consists of one comprehensive strategic project and two scientific–technical areas with six subordinated specific projects and connected by the before mentioned approaches of the Industry 4.0, see Figure 1 [2].

At the time of the project application development (i.e., in 2016), the European Commission had presented an ambitious new Circular Economy Package (on 2 December 2015) including a proposal for recycling targets for municipal (65% by 2030) and packaging waste (75% by 2030) [3].

Figure 1. Holistic approach of ReWaste4.0—interdependencies of the strategic project and both areas connected by the approaches of Industry 4.0 [2].

In the meantime, the most important action in European waste management was the adoption of the Circular Economy Package that came into force in 2018 [4]. The revised legislative framework on waste entered into force in July 2018 and, among others, it sets clear targets for selected waste, namely:

- 65% recycling of municipal waste by 2035;
- 70% recycling of packaging waste by 2030.

The dynamic change in the performance of municipal waste management for the EU 28 and the development needed to meet the recycling rates set by the circular economy package 2018 are shown in Figure 2.

Figure 2. Left: development of municipal waste management in the EU 28 from 1995 to 2017 with the forecasts (linear extrapolation, and potential development towards the minimum requirements of the new circular economy package) until 2035. Right: required development to meet the recycling targets [5], modified from [6].

Next, in 2019, the European Green Deal [7] was published. It is a roadmap for making the EU's economy sustainable. Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, Europe needs a new growth strategy that transforms the Union into a modern, resource-efficient and competitive economy where:

- there are no net emissions of greenhouse gases by 2050;
- economic growth is decoupled from resource use;

- no person and no place are left behind.

1.1. Municipal and Commercial Waste Management

Worldwide, 2.01 billion tons of municipal solid waste (MSW) from residential, commercial, and institutional origins were generated in 2016. This number is expected to increase substantially to 3.4 billion tons by 2050 [8].

In EU28, approximately 252 million tons of municipal waste were generated in 2018, i.e., 491 kg/capita and 47% of it was recycled [9]. Weißenbach et al. [10] report that an additional recycling potential of about 46.3 million tons of municipal waste by 2040 is available.

In Austria, on a federal level, there is no specific legislation on mixed commercial waste (MCW). The term “commercial waste” is not defined, neither in federal nor in provincial legislation. In the Austrian waste catalogue, ÖNORM S 2100 [11] based on Waste Catalogue Ordinance) commercial waste is assigned to waste group 91 “Solid municipal waste, including similar commercial waste”. A clear definition of MCW is given, for example, in Germany that has stipulated the Commercial Waste Regulation [12]. There, MCW is a non-municipal residual waste that is not collected separately, such as office waste, industrial waste, for example. Typical MCW can be characterized by low moisture content, high calorific value, low organic content, and high content of recyclables [13,14]. Owing to its energetically usable calorific value higher than that of mixed municipal waste, it is used to produce SRF [15–18]. The composition of MCW varies widely and depends on the industry in which it is generated [14]. Weißenbach [13] gives aggregated results of MCW sorting analyses in 2018 and 2019, see Table 1.

Table 1. Results on composition of mixed commercial waste from investigations made by Weißenbach [13] performed in 2018 and 2019.

Material Fraction	Weight Percent (%)	
	Site 1 (2 Experiments)	Site 2 (2 Experiments)
Plastics	19.1	16.2
Paper/cardboard	16.8	12.0
Metals	4.3	4.0
Wood	7.1	9.8
Inert	4.3	
Textiles	3.6	58.0
Others	44.7	
Total	99.9	100.0

The definition of mixed municipal waste (MMW), that is relevant for this paper is given in § 2, number 4, point 2 of the Austrian Waste Management Act 2002 [19]. There unprocessed mixed municipal waste is “waste from private households and other waste which, because of its nature or composition, is similar to waste from private households; the classification shall take into account the European Waste List as defined in Article 7 of Directive 2008/98/EC on waste. Mixed municipal waste within the meaning of the European Waste List shall continue to be regarded as mixed municipal waste even if it has undergone a treatment process which has not significantly altered its properties.” In contrast to MCW, MMW has a higher content of moisture, lower calorific value, higher organic content and quite lower recyclable content [20]. The composition of MMW depends on various factors including the available waste collection system, the socioeconomic structure of the population and/or the situation of urban or rural households.

The Federal Waste Management Plan (FWMP) of Austria provides extensive information on treatment plants as well as data on the composition of MMW and the contained share of potential recyclables for 2018, see Table 2 [21].

Table 2. Composition of mixed municipal waste and the contained share of recyclables in Austria for the year 2018 [21].

Material Fraction	Share (in %)	Sub-Total (in %)	Recyclable Quantity (in t)
Plastic—packaging	7.10		
Other light packaging	1.10	17.58	256,455
Plastic—no packaging	9.38		
Biowaste (incl. not avoidable food waste)	1.31	17.81	
Avoidable or partly avoidable food waste	16.50		
Paper and cardboard—packaging	2.20	13.96	203,647
Paper and cardboard—no packaging	11.76		
Sanitary products	9.64	9.64	
Textiles	7.79	9.79	
Shoes	2.00	5.86	
Inert	5.86		
Glass—packaging	3.80	4.86	70,897
Glass—no packaging	1.06		
Metal—packaging	2.50	4.70	59,373
Metal—no packaging	2.20		
Other waste	4.01	5.71	
Wood—no packaging	1.70		
WEEE	0.77		
Batteries, incl. accumulators	n.d.	1.54	
Hazardous household waste	0.77		
Others (not identifiable)	8.55	8.55	
Total	100.00	100.00	590,372

The shares of the potentially recyclable materials: plastic, paper/cardboard, glass and metal add up to 41.1%, equalling a total of 590,372 tonnes in 2018. Experience shows, however, that a lot of these materials cannot actually be recycled because of their low quality (e.g., contamination with dust, biodegradables, or moisture) [13]. According to the FWMP [21] mixed waste (MMW and MCW) and mixed outputs from treatment plants for source separated fractions like paper/cardboard, or plastics are treated in mechanical and mechanical-biological treatment plants and, there, SRF and other outputs are produced. The second option for treating of mixed waste is energy recovery in waste-to-energy plants.

As shown in Tables 1 and 2, a large amount of plastic is still available in mixed municipal and commercial waste as well as SRF and therefore it represents an important potential for further recycling processes.

1.2. Plastics and Their Importance in the EU

The European strategy for plastics [22] intends to transform the linear (make–use–dispose) economy of plastics into a more circular, resource-efficient system. Various policies have been put in place to achieve this goal; e.g., banning certain single-use plastic products, limiting lightweight plastic bags or creating quality standards for secondary plastics. Among others, mandatory recycling rates for plastic packaging (i.e., 50% by 2025 and 55% by 2030) were introduced. In order to achieve these ambitious recycling targets, the recycling of separately collected plastic packaging is not enough. Plastics must also be recovered from other waste streams. Due to the high volume of waste and the high unused plastics content, MCW and MMW would be suitable for this [20].

1.3. Digitalisation in the Waste Management Sector

In order to have a common understanding of used definitions, acc. to Tschandl et al. [23]:

“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”.

Then, Tschandl et al. [23] show that 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”.

Next, Tschandl et al. [23] summarize the term “smart factory” 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.”

Curtis and Sarc [24] as well as Sarc et al. [25] have introduced the term “Smart Waste Factory Network” (SWFN) that 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.”

To define the state of the art of digitalization on the waste management sector, Sarc et al. [25] gathered relevant contributions in literature via databases with the following relevant search terms (keywords): “digitalisation”, “robotics”, “smart waste”, “smart factory”, “industry 4.0”, “internet of things”, “waste management” and “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 2019), see Figure 3. In addition, detailed research has been conducted on existing technologies in the environmental field, with a focus on waste management [25].

Figure 3. Number of reviewed literature sources by type, assigned to peer-reviewed or non-peer-reviewed papers over the years 2001–2019 [25].

A total of 115 literature 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 results show that the topics digitalization 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 and others) [25].

Sarc et al. [25] report that “Big Data” is a fundamental element of digitalization and already a valuable raw material for many industries. In combination with “Artificial Intelligence” (AI), it is possible to structure, analyze, evaluate and use large amounts of data as a basis for software programs that can generate new (or extended) knowledge together with the aspects of “Machine Learning” as a part of AI. 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 Figure 4).

Figure 4. Digitalization along the value chain [26].

Abdallah et al. [27] have extensively investigated artificial intelligence (AI) applications in solid waste management and have found similar conclusions as Sarc et al. [25]. Abdallah et al. [27] report that MATLAB was the most common simulation software tool utilized in the waste sector. Next, Abdallah et al. [27] conclude that Artificial Intelligence-based solid waste management systems are still mostly in the research and development phase. Additionally, the most important limitations or challenges in waste management are, among others, insufficient amounts of data and its quality as well as the slow shift of waste management business entities in adapting towards the utilization of artificial intelligence versus traditional methods.

Finally, to simulate or carry out digital processes in waste management plants, large amounts of high-quality real, online/ontime data are needed as a basis. These data were gained within ReWaste4.0 based on practical, experimental as well as large scale tests in waste treatment plants.

As described, ReWaste4.0 is mainly focused on the treatment of mixed waste by applying Industry 4.0 approaches and the main focus of the present review-article is set on three categories of investigated topics:

1. Contaminants in mixed waste and technical possibilities for their reduction as well as removal;
2. Secondary raw and energy materials in mixed waste;
3. Digitalization in waste characterization and treatment processes for mixed waste.

Finally, the objective of the present review article is to summarize, link and discuss the main topics and results of the K-project and to discuss the main findings and their relevance as well as importance for further development of waste treatment sector. The review is executed mainly based on the peer-reviewed papers that have been published within the project.

2. Materials and Methods

A literature review mainly based on the peer-reviewed publications and selected conference contributions published within the project ReWaste4.0 (time period: 2017–2021) was carried out to focus on and discuss selected important results and findings of four years of cooperative research and development. Additionally, certain conference proceedings and peer reviewed papers not originating from ReWaste4.0, but with relevant information and impact on the topics of ReWaste4.0, were considered too.

3. Results and Discussion

As shown before, mixed waste such as Mixed Municipal Waste (MMW) and Mixed Commercial Waste (MCW) are the focus of research and development within the ReWaste4.0 project. Knowledge on the properties of such waste that serves as an input for mechanical waste treatment plants, however, is important for defining the number and processing depth of the required treatment steps as well as assessing the feasibly achievable quality of the output fractions. In order to characterize waste (plant's input and output) and to determine important parameters, e.g., heavy metal contents, material composition, or the mass share of valuable materials, sampling is still unavoidable for the state of the art. The main criterium that needs to be fulfilled by a sampling procedure is representativeness. With increasing material heterogeneity and particle sizes (note: they are large for MMW and MCW), more elaborated sampling procedures are required. Sampling procedures shall therefore follow the principles of the theory of sampling (TOS), which is an integral component of many internationally recognized waste sampling standards (e.g., EN15442:2011) [28,29].

Khodier et al. [30] and Viczek et al. [31] have determined the relative sampling variability (RSV) for material classes and chemical elements in different particle size classes of coarsely shredded MCW with a replication experiment. A total of 10 representative samples were taken and screened to yield 9 particle size classes. RSVs for material classes in different particle size classes ranged up to 231%, while RSVs for chemical elements ranged up to 203.5%. The RSVs for different chemical elements are depicted in Figure 5 and show that higher RSVs are tendentially observed for chemical elements with a higher constitutional heterogeneity, i.e., elements that occur in largely different concentrations in different particles. In general, far better RSVs were achieved when calculated for the original, mixed waste stream instead of the nine particle size classes.

Figure 5. Relative sampling variabilities (RSV) for different elements, lower heating value (LHV), ash content, and hard impurities (IMP) in different particle size classes. The solid grey line represents RSVs calculated for the whole waste mix, i.e., for the united particle size fractions [31].

The procedure for sampling and analysis, which was elaborated and evaluated in these publications almost completely eliminates incorrect sampling errors and suggests that grouping and segregation errors causing distributional heterogeneity significantly influence the results. Consequently, increasing the number of increments taken to reach the target sample mass is expected to have a larger beneficial effect than increasing the mass of the composite sample, which advantageously does not affect the efforts for analyzing the composite sample [30,32]).

Furthermore, Viczek et al. [31] combined the results obtained for the material composition and chemical analyses to assess whether a mathematical relationship between these parameters can be derived. A preliminary modeling approach shows that it may be possible to predict most element concentrations based on the material composition of MCW, which may be promising for quality assurance in MCW treatment plants, e.g., SRF and other waste fuel production plants.

Despite the mentioned challenges when dealing with coarse and heterogeneous waste like MCW, MMW and SRF, high-quality and representative results have been obtained and are presented in the following chapters.

3.1. Contaminants in Mixed Waste and Technical Possibilities for Their Reduction as Well as Removal

Contaminants play an important role for all waste treatment options, independent of the classification of treatment process as recovery (R) or disposal (D) operations according to the EU [33]. For the Austrian SRF industry, especially As, Cd, Co, Cr, Hg, Ni, Pb, Sb and Cl are relevant due to legal limit values [34] or technical requirements [35]. Viczek et al. [36] have identified the material fractions or products ending up in MCW or MMW that carry significant amounts of the above-mentioned nine elements, i.e., contaminant carriers. Their review showed that contaminant carriers in MCW and MSW are highly versatile. With respect to the Austrian situation, relevant contaminant carriers include PVC (Cl, Cd, Sb, Pb), flame-retardant plastics or textiles (Sb), rubber (Sb, Cl), glass (As, Co, Pb, Ni), leather (Sb, Cr), specific wood (As, Pb, Hg, Ni), electronic equipment and batteries (As, Cd, Cl, Cr, Co, Pb, Hg, Ni), shoes (Cd, Cl, Cr, Pb), or metals (Cr, Co, Pb, Ni). As many of these elements (Cd, Sb, Cr, Co, Pb) are used as pigments for ceramics or plastics, these products can be contaminant carriers as well. Furthermore, the literature review of [36] often identified the fine fraction with different particle sizes as important contaminant carriers for various elements, e.g., Pb, Hg, or Ni. This indicates that the relevant contaminants are not only enriched in specific materials, but also in specific particle size classes, which is why the distribution of various chemical elements among different particle size fractions of MCW was investigated [37].

Based on their particle size-dependent distribution, Viczek et al. [37] divided different elements into three groups:

- A: Negative linear correlation—higher concentrations in smaller particle size classes,
- B: No linear correlation—low concentration in smallest and largest particle size classes,
- C: Positive linear correlation—higher concentrations in medium to large particle size classes.

While As, Cr, Co, Pb, Hg and Ni belong to group A, Cd belongs to group B, and Cl, Sb, as well as the LHV were assigned to group C. This implies that these elements influence the output of a waste processing plant into different extents depending on the design of the process. The patterns for Hg and the LHV are depicted in Figures 6 and 7, respectively. Similar findings were also reported by Curtis et al. [38] who investigated four particle size classes of different samples of MCW and compared the concentrations in these particle size classes to the limit values of the Austrian WIO [34].

Figure 6. Concentrations of Hg in different particle size classes of mixed commercial waste and contribution of each particle size fraction to the total Hg load [37].

Figure 7. Lower heating value of different particle size classes of mixed commercial waste and contribution of each particle size fraction to the total LHV [37].

The results for the LHV, Cl, and Sb reflect the fact that plastics (which are rich in LHV and often contain Cl and Sb) are rather present in large particle size fractions, while smaller

particle size fractions rather contain larger amounts of biogenic or inorganic materials. Generally, Cl, Sb, and the LHV showed negative correlations with most other elements, while being positively correlated with each other. Furthermore, a strong positive correlation was observed for Cr and Ni, which are typical constituents of metal alloys.

The reported results on contaminants in different particle sizes from Viczek et al. [37] indicated that screening can be a suitable technique to (technically simply and financially reasonably) remove relatively large amounts of contaminants from the waste stream. Calculations showed that a theoretical removal of the fine fraction <5 mm or <10 mm results in significant decreases in the concentrations of Hg, Co, Ni, As, Cr, and Pb, but the Cd, Sb, and Cl concentration in the remaining waste is increased (Figure 8). However, this effect is compensated by the increasing LHV if the concentrations are considered in mg/MJ. As Cd, Sb, and Cl frequently occur in plastics, a combination of screening and targeted NIR sorting seemed to be a promising approach to decrease the concentrations of all relevant contaminants, which was tested by Viczek et al. [39].

Figure 8. Effect of the removal of the fine fraction <5 mm (a) and <10 mm (b) on analyte concentrations in mg/kg_{DM} and mg/MJ [40].

As noted before, the experimental investigations of Viczek et al. [39] demonstrated that a combination of screening with NIR sorting can decrease the Sb, Cl, and Cd content in the remaining waste stream. Especially the removal of the PVC fraction in combination with removing the fine fraction, e.g., <20 mm, can give good results with respect to the analytes. The removal of PET, in comparison, had rather low effects on the contaminant concentrations in the remaining waste stream. Removing PET and PVC, but not removing the fine fraction, in contrast, can result in an increase in the concentrations of some contaminants. Another fraction that contained large amounts of Cl, Sb, and Co were black and grey materials, but they cannot be identified or detected with conventional NIR sorters working in the range of 900–1700 nm. However, other technologies that may be able to remove these materials exist, and these materials require more attention and research in future [39].

However, while the quality of the screen overflow is increased concerning several parameters, the screen underflow represents a waste fraction with poor quality and a low LHV, exceeding selected limit values, e.g., those for SRF defined by the Austrian WIO [34]. Nevertheless, at the same time, it contains mineral matter that can substitute primary raw materials and be recycled in the cement industry (see Section 3.2), which leads to a so-called “conflict of interests” between environmental protection and resource conservation/utilization.

In conclusion, contaminants frequently occur in a broad range of products and therefore waste management needs to deal with them on a daily basis. For this reason, existing, arising and future recycling concepts, e.g., chemical recycling, need to enable high recycling rates while also providing quality oriented and assured recycling.

3.2. Secondary Raw and Energy Materials in Mixed Waste

Here, the focus is given to plastics and SRF as well as their co-processing, mainly in the clinker production process of the cement industry.

3.2.1. Plastics

The content of plastics in MMW and MCW acc. to Weißenbach et al. [14] and Möllnitz et al. [20] is about 15% for MMW and between 15% and 23% for MCW. Both types of waste are treated in splitting plants or mechanical–biological plants for, among others, the production of SRF or in thermal plants (with and without energy utilization) (note: in selected EU countries including Austria, direct landfilling of untreated MMW and MCW is legally forbidden). For a further, more efficient, recovery of the plastics contained in these wastes, it is necessary to know and understand in which geometric dimension (two-dimensional/three-dimensional) and in which particle size range they are present after pre-shredding—which is usually the first processing step in mechanical processing, targeting the comminution and liberation of waste particles according to Khodier et al. [41].

The investigations on total composition of plastic content of MMW and MCW after pre-shredding and screening of fine fraction have shown that a screen cut at 20 mm removes about one third (MCW: 33%; MMW: 37%) of the total material after pre-shredding. This fine fraction has a high inert, contaminant and organic content [20,36] and is therefore unsuitable for plastics recovery.

The results given in Figure 9 show that MCW has a twice as high plastics-3D content as MMW. The plastics-2D content (e.g., foils), on the other hand, is similar in both mixed waste types. A particle size dependence of the dimensionality of the plastic particles can also be seen for both wastes: the share of 3D particles is higher in small particle size classes, while in large size classes more 2D-plastics are found. This information is relevant for treating the waste stream in a targeted and efficient way and to be able to separate the desired fraction at the proper process step. For further processing, the particle shape is also of high importance for the separation and sorting success and the associated purity of the targeted fraction (e.g., flight behaviour of films in NIR-sorting) [20].

Figure 9. Content of plastics-2D and plastics-3D in mixed commercial waste (a) and mixed municipal waste (b) in different particle sizes [20].

Figure 10 shows the results of the sensor-based sorting by NIR of each individual particle size class into its plastic types and remaining components using MCW as an example [20]. The results show that certain types of plastics are more common in distinct particle size classes than in others and that this is also dimensionality dependent. This information is important for further increasing the purity of extracted plastics by efficiently routing those material flows that have high concentrations of plastics or specific plastic types.

Figure 10. Particle size distribution in investigated material types for plastics-2D (a) and plastics-3D (b) normalized to 100% for mixed commercial waste [20].

The presented results clearly show that there is a high, as yet unused potential of plastics in the two mixed waste types investigated. For the efficient recovery of certain types of plastics, early screening of the fine fraction after pre-shredding makes sense in order to remove contaminants and impurities (see also Möllnitz et al. [42]). A targeted material flow division according to dimensionality (e.g., using a ballistic separator as it is proposed by Möllnitz et al. [42]) as well as further screen classifications into specific particle size classes are necessary to achieve the targeted concentration of plastics and to make sensible use of plant capacities. In order to be able to implement this processing step in a real waste processing plant, it is therefore necessary to know the respective waste in detail.

The plastic concentrates produced in the waste sorting plants usually still have a high amount of impurities and contaminants. These can be of organic (e.g., other plastics, adhering oils or fats) or inorganic (e.g., metallic coatings) origin [43]. In order to meet the quality requirements of the recycler for the flakes and those of the plastics processor for the granulate produced, subsequent wet processing at the plastics recycler site is usually necessary [44]. A benchmark analysis [44] was carried out with data from experts and stakeholders in Austria and Germany to determine the correlation between different quality features and how they affect the pricing policy for recyclates. Several quality assurance measures are carried out along the value chain from plastic waste to final plastic products. The most important quality assurance parameters and how they (would) affect prices of recyclates were investigated. Friedrich et al. [44] report that pricing correlates with different quality parameters such as degree of mixing, degree of degradation and presence of impurities and contaminants and that the origin of waste affects the assessment of the sorted plastic waste quality. Next, the physical, rheological and mechanical properties of the recyclates are of great interest and the following characteristics were analyzed in the course of a random sample inspection:

1. physical properties like density determination;
2. rheological properties like melt-mass flow rate;
3. mechanical properties like tensile properties, especially modulus of elasticity and notch impact strength.

Frequently, further parameters of the recyclates are determined. These include [44]:

- melting temperature;
- colour distribution and colour composition;
- size and form of the granulated material (e.g., lenses, cylinder);
- moisture content;
- filtration fineness;
- ash content;
- heavy metal content.

To investigate plastics from MMW and MCW regarding the aforementioned requirements, the processability of different polymer fractions from mixed waste was examined and the determination of material properties for recycling was carried out by Möllnitz et al. [45]. For the investigations, commercially available SRF and two mixed polyolefin (PO) fractions (polyethylene—PE and polypropylene—PP) obtained from MMW and MCW treatment processes were used. In addition to a different processing depth (washed and unwashed) of the inputs, the focus of the investigations was the processability of the recovered plastic types (PE, PP, polyethylene terephthalate (PET), polystyrene (PS) see Figure 11) and plastic mixtures (PO and SRF) in a compression molding process (with and without previous homogenization in an extruder) and their characterization regarding the following parameters:

- Thermal properties: determination of the crystallization temperature (T_C) with the respective crystallization enthalpy (ΔH_C), melting temperatures (T_{m1} and T_{m2}) with the respective melting enthalpy (ΔH_{m1} and ΔH_{m2}), and the glass transition temperature (T_g) with differential scanning calorimetry (DSC);
- Mechanical properties: impact strength and notched impact strength, tensile test (Young's modulus (E), tensile strengths (σ_M), elongations at break (ϵ_B)), bulk density of flakes after shredding and granulate after extrusion, determination of ash content;
- Rheological properties: melt flow rate (MFR) [45].

Figure 11. Exemplary photos of plastic types sorted with NIR: PE—(A); PP—(B); PET—(C); PS—(D); and others—(E) [45].

The main results of the investigations in Möllnitz et al. [45] are: except for PET, all plastic types and mixtures were processable (extrudable and/or compressible). Both the flakes

and granulates showed good feeding and conveying behavior. The thermal properties were generally good and indicate little material damage but organic impurities present. The heating and cooling curves were particularly reproducible for the heterogeneous materials. The results of the mechanical properties show a clear material embrittlement due to existing impurities (especially for the PS materials). Furthermore, it was found that washing does not always lead to a significant improvement of the mechanical properties. It could also be shown that sorting into certain plastic types, such as PE and PP, is not necessary for certain applications, as the PO and mixed plastic fractions investigated have a good mechanical property profile.

Regarding processability of the mixed waste (MCW and MMW) with focus on plastics recovery, the following technologies were investigated and the results were obtained:

1. Dry mechanical waste treatment with pre-screening prior further processing by ballistic separation and sensor-based sorting for generation of a 3D plastics pre-concentrates for recycling [42].

Large-scale experiments with mobile machines were conducted to investigate the influence of an upstream drum screen on the downstream process and sorting quality of 3D-plastics when processing MCW and MMW. For each input waste, two tests were carried out with and without a drum screen. A mass balance was determined for each test run and the screening efficiencies (drum screen and ballistic separator) were calculated. All generated outputs were sampled and subjected to an extensive screening and sorting analyses. The main results of the investigations in [42] are:

The mass balances (see Figure 12) show that for both wastes, a slightly increased 3D yield (2–5%) with a simultaneously reduced 2D yield (approx. −20%) due to upstream drum screening on the ballistic separator result were produced. Pre-screening (doubling the active screen area) improved the overall screening efficiency up to 0.99 and increased the total fines yield (<80 mm) by 10–15%. In addition, it was found that the combination of selective comminution and pre-screening resulted in the screen fines having a higher contaminant, inert and organic content per lower calorific value than the ballistic separator fines [31]. The ballistic separator fines consisted of more near mesh size particles of plastics and other valuable materials with higher calorific value. As Möllnitz et al. [20] show, this particle size fraction still has a considerable plastics potential and could be used for plastics recovery for recycling or SRF production.

Figure 12. Mass balance for test run 1 with mixed commercial waste [42].

The manual sorting analyses of the 2D fractions show a reduction in inert (up to −50%) and fines (<80 mm) (up to −75%) by pre-screening. Especially in the test runs with MCW, tail formations were observed in the drum screen, which led to material losses, false discharge into the 2D-fraction and plant downtimes. The manual sorting analyses of 3D fractions show a very low amount of 2D and fines. This confirms the optimum operation type for producing a 3D fraction with high purity. Applied pre-screening improves the NIR-sorting efficiency (yield) of 3D fraction by 6%, see Figure 13.

2. Wet mechanical processing of plastic rich 2D-fractions with a focus on polyolefins (POs) from mixed waste for chemical recycling [46]:

Figure 13. Effects of pre-screening on purity (a) and yield (b) of the 3D-plastics out of the 3D-fraction from the ballistic separator of the investigated mixed commercial waste [42].

The potential and applicability of a dry-mechanical (materials from investigations presented in Möllnitz et al. [46]) and subsequently wet-mechanical processing with the aim of generating a PO concentrate for chemical recycling purposes was assessed. The focus of the investigation was the wet density separation by using a centrifugal force separator (CFS) [47] as the core element of the wet-mechanical process. The fed material is separated according to its density in the separation medium water in a feed-related air/water vortex and discharged as heavy and light material. The light fraction out of the first run was fed into the centrifugal force separator (CFS) once again, simulating a cascade connection of two CFS plants to achieve a further concentration of the POs. The required process water circulated throughout the entire experiment and was only replaced by freshwater when the material was changed. The process water was collected and decoupled from the treatment line and fed to a static drum filter to separate the liquid and solid phases. The mass balances for both input materials and both test runs were calculated. The input material, all output materials (light and heavy fractions, sediment) and the process waters were sampled and chemically and physically characterized to estimate potential treatment or recycling paths.

For an evaluation of the suitability of the PO-fraction (light fraction two-LF II) produced as input material for the thermochemical conversion process (ReOil process), the measured values were compared with the quality limit values in Table 3. The specified particle size and bulk density range were achieved through targeted pre-treatment for both waste fractions. The limit value for the moisture content was not met as only one linear vibrating screen was available. The limit values for the calorific value and the chlorine content were met for both waste fractions. The required content of PE, PP, PS is also met for both waste fractions within the assumption made. Since the total contaminants contained in both fractions exceed 3%, compliance with the required limit values for polymer impurities, inorganic and organic contaminants is not guaranteed.

In summary, all the results from this chapter show that the recovery, treatment, and processing of plastics from non-hazardous, mixed, solid waste for mechanical or chemical recycling is possible. By transferring these plastics from thermal treatment to recycling purposes, an important contribution is made for achieving the recycling targets, resource conservation, and reducing greenhouse gases and waste.

3.2.2. Solid Recovered Fuels (SRF)

SRF has been defined by the CEN/TC343 in the standard EN 15359:2011 [49] as fuel that fulfils following four criteria:

1. It is solid fuel;
2. It is prepared from non-hazardous waste only;
3. It is to be utilized for energy recovery in incineration or co-incineration plants;

4. It must meet certain quality criteria (i.e., lower heating value (expressed as mean), chlorine content (expressed as mean) and mercury content (expressed as median and 80th percentile value) and to be allocated in one of total five classes depending on the measured values for each mentioned parameter.

Table 3. Comparison of the measured values with the quality requirements for the ReOil process (MMW: mixed municipal waste, MCW: mixed commercial waste, CFS: centrifugal force separator) [46].

Parameter	ReOil-Process [48]	LF II MCW	LF II MMW	Comments
Particle size (mm)	<30–40	<20	<20	required particle size for CFS processing.
Bulk density ($\text{kg m}^{-3}_{\text{DM}}$)	50–100 (mainly 2D-objects)	approx. 80	approx. 60	was determined in [46].
Moisture content (%)	<20	49.5	67.1	additional dewatering equipment is required.
Calorific value ($\text{MJ kg}^{-1}_{\text{DM}}$)	>30	38.3	35.1	
Chlorine content (‰_{DM})	<2	0.2	0.47	
PP, PE, and PS content (%)	>90	95.8	94.9	assumption that the LFII consists only of PE, PP and PS.
Polymer impurities (‰_{DM})	PET: ≤ 3 ; PVC: ≤ 2			
Inorganic contaminants (‰_{DM})	≤ 3	4.2	5.1	total contamination content.
Organic contaminants (‰_{DM})	≤ 5			

In Austria, SRF is defined as “... waste that is used entirely or to a relevant extent for the purpose of energy generation and which satisfies the quality criteria laid down ...” [34,50]. Quality criteria that are limits for antimony, arsenic, lead, cadmium, chromium, cobalt, nickel and mercury and are expressed as amount per energy content (i.e., pollutant content per net calorific value related to dry matter— mg/MJ_{DM}) [34].

Sarc et al. [15–18] and Lorber et al. [35] report that the production, quality and quality assurance as well as utilization of SRF in the cement industry has become state of the art and even thermal substitution rates of up to 100% [51] can be technically reached. The data for 28 years (1998–2018) on the average thermal substitution rate (TSR) of SRF in the cement industry in different countries, the EU and worldwide show very positive and dynamic development [29,52], see Figure 14. As shown for 2018, the following TSR were reached: worldwide 18.5%, in the EU28 47.7% and in selected countries like Germany (68.6%) and Austria (81.1%).

Sarc et al. [17] report regarding two main types of SRF for the cement industry, namely, SRF PREMIUM Quality and SRF MEDIUM Quality and Viczek et al. [53] additionally give the definition of these two types as follows:

- SRF for secondary firing (SRF “secondary”): SRF with a lower heating value between 12 and 18 MJ/kg_{OS} (corresponding to class NCV 3 or 4 in EN 15359) suitable for the use in secondary firing (calciner, kiln inlet, or hot disc combustion chamber, etc.) in the kiln system of cement manufacturing plants. Particle sizes can range up to 80 mm when used in a calciner or at the kiln inlet and up to 300 mm for a hot disc combustion chamber.
- SRF for primary firing (SRF “primary”): SRF with a lower heating value between 18 and 25 MJ/kg_{OS} (corresponding to class NCV 1, 2, or 3 in EN 15359), and particle sizes below 30 (35) mm suitable for the use as a main burner fuel in the rotary kiln of cement manufacturing plants.

Figure 14. Development of the thermal substitution rate (in %) of SRF in the cement industry in different countries, the EU, and worldwide for the time period 1990–2018 [29,52].

Sarc et al. [17] extensively report the chemical–physical quality of SRF “secondary” and SRF “primary” currently available on the middle European market and conclude that SRF coming from multi-stage waste processing plants fulfil the Austrian legal and international SRF and co-incineration market requirements. On one side, SRF contributes to the energy production in the clinker process and, on the other side, as its ash can provide selected secondary raw materials for the production of clinker, SRF can be seen as “co-processed” in the cement industry. Co-processing is a term that comprises industrial processes that simultaneously enable energy recovery and recycling of the constituents [53].

3.2.3. Co-Processing of SRF–Ash Constituents of SRF as a Valuable Secondary Raw Material

The main raw materials required for the production of cement clinker are CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 . A typical composition of raw meal for production of Portland cement clinker is: 77.36 wt% of CaCO_3 , 13.73 wt% of SiO_2 , 2.93 wt% of Al_2O_3 , 1.84 wt% of Fe_2O_3 , 1.83 wt% of MgO , 1.08 wt% of SO_3 , 0.85 wt% of K_2O , 0.14 wt% of Na_2O , 0.02 wt% of P_2O_5 , 0.15 wt% of TiO_2 , 0.06 wt% of Cl and 0.01 wt% of ZnO [54]. A part of the required raw materials can also be provided by SRF ash, which is incorporated into the clinker and thereby recycled when SRF is co-processed in the cement industry.

To determine the material-recyclable share (R-index) of SRF, Aldrian et al. [55] have developed and validated an analytical method for the determination of the ash composition and have proposed a formula to calculate this R-index. Average ash composition (arithmetic means) of SRF primary and SRF secondary is given in Figure 15. Different R-indices are achieved when different element oxides are considered [53]: For example, when considering only Al_2O_3 , CaO , SiO_2 , and Fe_2O_3 , R-indices of 13.9% (SRF secondary) or 13.3% (SRF primary) are achieved. When additionally, MgO , TiO_2 , K_2O , Na_2O and SO_3 are considered, the R-indices rise to 16.2% for SRF secondary or 15.9% for SRF primary. When the whole ash content is considered as recycled, the R-index amounts for 17.7% (SRF secondary) and 17.6% (SRF primary).

Figure 15. Average ash composition (arithmetic means) solid recovered fuel (SRF) primary (a) and secondary (b) in mass percent dry mass [53].

The average SiO₂: CaO: Fe₂O₃+Al₂O₃ ratio reported by Viczek et al. [53] is depicted in Figure 16. On average, the share of SiO₂ is slightly higher in SRF secondary than SRF primary. Generally, the ratio of these element oxides in SRF ash is similar to lignite coal, SRF primary is even closer to sewage sludge. However, the higher share of CaO shifts many SRF samples closer to the desired ratio in clinker.

Figure 16. Ternary diagram illustrating the solid recovered fuel (SRF) ash composition of 80 investigated SRF samples and their average composition compared with other relevant raw materials and fuels [53].

A more detailed analysis of the ash of different SRF fractions and specific material fractions extracted from SRF, performed by Viczek et al. [56], shows that the highest material-specific R-indices are achieved for the fine fraction <10 mm, composite materials, or the sorting residue, see Figure 17. All these fractions are highly heterogeneous, and data from other established recycling processes are not yet available.

Figure 17. Calculated R-Indices for solid recovered fuel (SRF) sorting fractions (left) and specific materials extracted from SRF (right) for three scenarios considering different element oxides [56].

Consequently, when SRF is utilized in the clinker production of the cement industry, not only is the energy recovered, but also minerals from SRF ash are recycled by being incorporated into the cement clinker. This implies that the locally or regionally organized recycling and thermal recovery of SRF in the cement industry, commonly referred to as SRF co-processing, is a significant contribution of waste management for the globally producing cement industry.

3.3. Digitalisation in Waste Characterization and Treatment Processes for Mixed Waste

As mentioned before, Sarc et al. [25] report that digitalization in the waste management sector in comparison with other industrial sectors is still in its infancy. Nevertheless, “Digitalisation” and “Industry 4.0” approaches are of high interest in waste management and a survey carried out in 2017 shows that 63% of companies see digitalization as a chance for their further development [57].

Here, selected results at different levels of digitalization are given, namely:

- Digitalization as a modern tool for innovative data-based development of smart processes;
- Online–On-time material particle characterization and quality assurance;
- Experimental monitoring of waste flows and machine performance in waste treatment plants.

3.3.1. Digitalization as a Modern Tool for Innovative Data-Based Development of Smart Processes

Real-time (smart) process control for waste processing plants—but also in general—requires three fundamental elements (see Figure 18), according to Khodier [32]: “metrology that measures the state and performance of the process, algorithms that calculate optimal factor settings from the measurements, and actuators, like a shredders gap width, that function as change-

able factors for influencing the process". Due to the variety and complexity of waste as a material, the issue of online-measuring material qualities is a highly relevant topic in current research.

Figure 18. Trinity of real-time process control [32].

The mechanical treatment of mixed solid waste involves a variety of processing machines, e.g., shredders, screens and magnetic separators. Understanding the influence of their parameters (like the gap width of a coarse shredder) on the process is essential for the optimized operation of the treatment plants—in terms of process properties, like the throughput, but also concerning produced material qualities.

Nevertheless, waste processing machines are often tested and operated at fixed parameter settings, chosen by experience and intuition, without any physical or statistical proof of optimality, as Khodier [32] points out for coarse-shredding. A main reason for this unsatisfactory status quo is the complexity that is involved in reliable investigations on mixed solid waste processing.

Khodier et al. [41] discuss that physics-based numerical studies are hardly usable for investigations on the real-scale behavior of waste processing machines—the variability of waste and the diversity of materials and shapes hardly allows collecting the necessary information on the material to be processed. Therefore, while physical models are favorable in terms of the detailed process insights they provide, alternatives are needed.

Empirical modeling is a useful approach for, nevertheless, drawing reliable conclusions on mechanical treatment processes for mixed solid waste: a configurable set of parameters is chosen as factors to be investigated, concerning their effects on a set of chosen target values. Remaining parameters—like the composition of the waste, that cannot be controlled in detail—are treated as distortion in the data. In the presence of a sufficient amount of data, true effects become significant in a subsequent analysis of variance (ANOVA) and can hence be distinguished from data noise and quantified with corresponding confidence and prediction regions.

While empirical modeling itself is not novel, to the best of the author's knowledge, no industry-scale parameter studies on solid waste processing that comprehensively incorporate statistical analyses on significance were available when ReWaste4.0 started in 2017. Potential reasons include the tremendous efforts involved in generating a sufficiently large amount of real-scale data, the complexity of material analyses, that include considerations on waste sampling, and the non-triviality of modeling non-scalar target values, i.e., particle size distributions.

As a necessary precondition for generating the data to consider product qualities in empirical models, Khodier et al. [30] established a procedure for sampling coarsely shredded mixed commercial waste that comprehensively incorporates the theory of sampling,

while referring to the Austrian standard ÖNORM S 2127 for the calculation of total sample masses. Different to existing standards and literature, they did not only define and evaluate the sampling procedure based on theory, but also empirically quantify sampling errors, by comparing the shares of particle size-material fractions, determined from 10 samples of the identical material in a so-called replication experiment. Their results obtained are shown in Table 4. As can be seen, sampling errors are relatively low for the shares of the overall particle size distribution and the overall material composition but become much higher as the level of detail is increases—which decreases the shares of the analytes.

Table 4. Relative sampling variabilities (RSV) for various particle size classes and for the material classes metal (ME), wood (WO), paper (PA), cardboard (CB), 2D plastics (2D), 3D plastics (3D), inert materials including glass (IN), textiles (TX), and a residual fraction (RE) [30].

Particle Class (mm)	ME (%)	WO (%)	PA (%)	CB (%)	2D (%)	3D (%)	IN (%)	TX (%)	RE (%)	Sum (%)
0–5	-	-	-	-	-	-	-	-	12.3	12.3
5–10	-	-	-	-	-	-	-	-	12.3	12.3
10–20	-	-	-	-	-	-	-	-	10.4	10.4
20–40	41.4	17.7	24.3	39.3	18.4	17.1	19.7	29.3	22.7	11.6
40–60	47.3	21.5	16.8	25.6	14.2	8.7	37.2	43.4	16.4	8.8
60–80	39.4	23.3	22.9	18.1	17.7	10.0	49.9	30.4	8.9	8.1
80–100	62.0	34.7	38.0	14.2	19.3	17.5	210.7	43.4	17.2	7.7
100–200	74.0	47.7	69.0	21.6	28.9	35.2	131.8	40.9	40.0	10.9
200–400	153.0	230.9	203.9	126.2	38.3	39.8	-	42.9	52.2	28.8
Sum	16.4	18.3	10.5	15.0	16.6	12.1	31.2	26.6	3.6	0.0
RSV < 20%			20% ≤ RSV < 50%			RSV ≥ 50%				

Conclusive evaluations, that consider calculations of theoretical sampling errors, finally show that in the applied procedure, the so-called fundamental sampling error only explains a small share of the sampling variability. The authors conclude that grouping and segregation errors are likely to contribute a significant share—hence a higher number of increments at an unchanged total sample mass is expected to increase sampling quality.

Sampling errors, but also inter-experimental differences in the waste, lead to a considerable residual distortion of the data, when investigating influences of machine parameters. Considering the high efforts and costs of real-scale waste processing experiments, methods for increasing the efficiency of the data, in terms of extractable information per experimental run, are required. The publication of Khodier et al. [41] addresses this very interesting topic: they empirically model the influences of coarse shredders' radial gap width, shaft rotation speed, and three different cutting tool geometries, based on a 32-run Design of Experiments-based investigation, designed in consideration of a reduced cubic polynomial design model.

Design of Experiments targets increasing the efficiency of the data. The work of Khodier et al. [41] gives a general introduction into the method, while also discussing in detail the choice of the chosen experimental design (a so-called D-optimal design) and the design model. Their publication is hence an important reference as a “starting point” for incorporating empirical modeling in mechanical waste processing investigations.

Besides the provided proof of the potential of their chosen methods, the referenced work also provides quantitative conclusions on the influences of the described factors on the throughput (in terms of mass and volume), the throughput steadiness (in terms of the quotient of the 10th and 90th percentile mass flow and volume flow) and the specific energy demand. The results for each factor—under average settings of the corresponding other two factors—are shown in Figure 19, while the publication provides additional insights on an interdependence of the influences of the gap width and cutting tool geometry.

Figure 19. Effect plots with confidence bands for the influence of the gap width, shaft rotation speed, and cutting tool geometry on throughput, throughput steadiness, and specific energy demand, at average settings of the respective other factors [41].

Eventually, Khodier et al. [41] conclude that the cutting tool geometry is the factor with the highest influence and cannot be compensated by the easily changeable settings of the gap width and shaft rotation speed. Finally, they point out that an overall determination of economic optimality must evaluate the effects of the modeled target values on the (monetary) performance of the overall processing plant.

The modeled process properties must always be evaluated in combination with the properties of the processed material: the particle size distribution of the waste is an essential quality parameter of the processing product, and also influences the performance of the whole treatment process, as Khodier and Sarc [58] point out. They published an extension of the methods described by Khodier et al. [41] on non-scalar target values, i.e., particle size

distributions. They first give a comprehensive overview on classical descriptive methods for particle size distributions, e.g., particle lists, summary values, or analytical probability density functions. However, they find out that none of these allows the distribution-independent modeling of particle size distributions—which is essential for covering all kinds of processes—while always preserving all relevant information.

As a solution, they transfer methods from the field of modeling and analysis of compositional data: they model the particle size distribution through a multivariate multiple linear regression of isometric log-ratio-transformed shares of a deliberate choice of particle size classes. Isometric log-ratios free the data from the constraints of a simplicial vector space (all shares are positive, and their sum is constant), through a bijective projection on the one-dimension lower real space, hence allowing the application of standard statistics. To account for the interdependence of the particle size classes' shares, they furthermore involve the multivariate character of the data in all evaluations, hence evaluating factor significances through a multivariate analysis of variance (MANOVA).

Concerning the evaluated process—coarse-shredding of mixed commercial waste—Khodier and Sarc [58] find that, from the three examined factors, only the cutting tool geometry significantly changes the shares of three particle size classes (>80 mm, 30–80 mm, 0–30 mm), which were chosen based on their relevance concerning SRF qualities [17]. One remarkable conclusion—in consideration of the results of Khodier et al. [41] is that larger gap widths lead to higher throughputs and lower energy demands (which is both desirable) while not (negatively) affecting the material quality.

3.3.2. Online-Online Material Particle Characterization and Quality Assurance

Kandlbauer et al. [59] address the field of metrology, targeting the online-measurement of shredded mixed commercial waste's particle size distribution, as defined by a drum screen. In their approach, particle sizes are determined through a partial least square regression (PLSR) model, that is based on geometric descriptors of the particles' shapes, which were derived from two dimensional RGB (red—green—blue) images of single particles. Such two-dimensional images can be obtained in real-scale processing plants, by accessing RGB sensors on the acceleration conveyor belt of sensor-based sorters. Potential geometric descriptors were collected in a literature research: they include, for example, smallest enclosing polygons (e.g., triangles, circles, rectangles), and Feret diameters. A Partial Least Squares Regression (PLSR) finally uses these in a combined model, that keeps the number of empirical model constants low.

Kandlbauer et al. [59] conclusively find, that—while there are still unanswered questions, e.g., concerning image quality—when individually considering different material fractions, the performance of the models is very promising, with average errors of 0.2% for the shares of the particle size classes of wood for example, in the case of a uniform distribution. However, they also motivate for follow-up research to increase the accuracy of the measurements of individual particles, to ensure a distribution-independent good performance of the method—e.g., by evaluating the performance of machine learning models.

As described before, real-online/online and high-quality data are important in development of digitalized solutions for the waste management sector and especially in case of a so-called smart waste factory of the future. Various sensors are applied to measure waste data. Therefore, through ReWaste4.0 a new level of waste material characterization has been introduced for mixed waste, namely the characterization of mixed waste at a waste particle level and the target is to apply this approach online (i.e., real-time) and online (i.e., directly before and after each processing step and in case that such intensive monitoring is not possible to be carried out in a waste treatment plant, then at least input and output qualities should be monitored). Therefore, on one side monitoring of waste treatment processes can be executed and on the other side a quality assurance concept for waste materials can be carried out. This approach would deliver data for “intelligent communication” between material quality and machine as well as plant performance as aimed by ReWaste4.0 [2].

Weissenbach [60] report that there is no general definition of the term “waste characterization” but this procedure is applied for a number of different purposes. Typical aspects of the waste characterization procedure are the definition of waste composition based at the material type level as well as chemical and physical investigations for definition of waste properties. Furthermore, more technological methods of waste characterization are realized by applying sensor technologies (cf. [25,61,62]) as well as RGB cameras (cf. [59]).

As described by Weissenbach and Sarc [60,63], the investigation has been carried out at the level of individual particles and a total of eight fractions have been characterized, namely: paper/cardboard, wood and liquid packaging board (LPB) as well as plastic fractions PE, PP, PS, PET and polyvinyl chloride (PVC). Selected parameters are the projected particle area and the particle mass. In total, 15,542 particles of fine SRF (<30 mm) have been investigated. Next, single particles from SRF with particle size 30–80 mm (1,078 particles investigated) as well as a pre-treated MCW fraction with particle size 80–500 mm (1,268 particles investigated) have been examined [63]. All data have been statistically assessed and, in summary, the following results have been gained, see Table 5. As shown, the projected area value for pre-treated MCW is 10 times bigger than the value for SRF secondary and this, in turn, is 3 to 4 times bigger than the value for SRF primary. For the mass, the values have factors of 13 to 14 (pre-treated MCW vs. SRF secondary) and of about 6 (SRF secondary vs. SRF primary) [13,60,63].

Table 5. Median of the projected area and particle mass, classified according to particle size classes and material fraction [13,60,63].

Material Fraction	SRF Primary		SRF Secondary		Pre-Treated MCW	
	Proj. Area (in cm ²)	Mass (in g)	Proj. Area (in cm ²)	Mass (in g)	Proj. Area (in cm ²)	Mass (in g)
Paper	4.1	0.14	13.8	1.17	168.9	15.4
Wood	1.4	0.14	6.4	1.62	72.9	57.7
LPB	3.8	0.17	19.5	2.66	131.4	24.0
PE	5.4	0.15	15.8	0.64	198.9	5.3
PP	4.2	0.23	11.8	1.37	124.6	9.3
PS	3.2	0.19	12.6	1.04	68.1	8.9
PET	4.4	0.30	9.0	1.46	135.4	21.1
PVC	3.4	0.23	11.0	2.17	64.4	24.9
Total median	3.6	0.19	11.5	1.21	114.2	16.65

3.3.3. Experimental Monitoring of Waste Flows and Machine Performance in Waste Treatment Plants

Sarc et al. [25] report that, in most waste treatment plants, a typical weighbridge is used for measuring of input and outputs but, in the technical process itself, there is no online and ontime mass or volume flow measurement introduced. Additionally, in many cases the shovels of wheel loaders are equipped with weighing devices for a rough determination of a throughput. However, these methods do not allow machine, process and/or plant real-time (ontime) monitoring. As stated in the paper, the retrofitting of machines, processes and/or plants with volumetric flow measuring systems seems to be a promising approach as its installation would not need process concept changes but relatively simple mounting over the conveyor belts. However, to be able to convert these measured volume flow data into mass (i.e., tones) data, the bulk density of the material at every installed position is to be determined. When processing mixed waste like MMW, MCW, SRF, it has to be noted, as described before, that the composition and fluctuations in its composition as well as the properties of such waste are constantly changing and therefore, a continuous measurement in order to calibrate the system in real time is required.

Curtis et al. [64] and Curtis and Sarc [65] have extensively investigated these fluctuations in a semi-large scale “Technikumslinie4.0” (technical production line 4.0) and large-scale experiments and based on results made a distinction in:

- Short-term fluctuations (expressed as throughput change in intervals <15 s);
- Mid-term fluctuations (expressed as throughput change in intervals of 15–600 s);
- Long-term fluctuations (expressed as throughput change in intervals >600 s).

As proven by experiments from Curtis et al. [64] and Curtis and Sarc [65], short-term fluctuations resulted mostly from material's composition, constitution and its particle size characteristics and machine specific parameters (e.g., drum screen speed, reversing intervals of shredders). Mid-term fluctuations originated especially from a discontinuous feeding process with the wheel loader or other feeding machines. Long-term fluctuations would be in a range of >600 s or longer and result from changes in machine parameter—while testing, no such fluctuations were recorded as all shredder parameters were kept constant. Additionally, fluctuations were investigated regarding their influence on the performance of selected (subsequently positioned) machines like the sensor-based-sorting machine as well as a monitoring unit after a shredding step to combine the measured data on volume flow fluctuations with the power consumption of the shredder. Results show that fluctuations in throughput can be measured by volumetric flow measuring systems which ensure the availability of selected information for a better understanding of the treatment process and its conditions. Next, fluctuations have significant influence also on the performance of the subsequent machines and can directly influence the product quality and the therewith connected market value of the product. Finally, the combination of online and ontime material flow and composition monitoring systems (before and after a machine) with machine (note: conveyor belts are also to be considered as “machines”) consumption (e.g., energy), machine settings and performance control, both systems equipped with proper data collection, analysis and management as well as digital interconnection tools, can contribute to the further development of the so-called Smart Waste Factory for the waste treatment sector.

4. Conclusions

Within the current FFG-funded COMET K-Project “ReWaste4.0”, two scientific and eight company partners initiated in 2017 the ambitious and required paradigm shift for the transformation of the non-hazardous mixed municipal and commercial waste management towards a Circular Economy 4.0. ReWaste4.0 and the approved follow-up project “Recycling and Recovery of Waste for Future (ReWaste F—2021–2025), among others, are future oriented projects that are based on legal developments in the EU, especially Circular Economy Package from 2015 and 2018 and European Green Deal from 2019 as well as market developments regarding digitalization and Industry 4.0 approaches.

As shown in the present review-paper, Circular Economy 4.0 involves a better understanding of contaminants contained in products and waste (note: every product will finally become a waste material—it is just a question of time!), deeper know-how on secondary raw and energy materials as well as co-processing materials and application of digitalization and Industry 4.0 approaches in waste characterization and the waste treatment sector.

When dealing with mixed waste like MMW and MCW with high material heterogeneity and various as well as large particle sizes, representative sampling and analysis of such waste is of high priority as the results influence all further steps. Therefore, within ReWaste4.0 the principles of the theory of sampling and internationally recognized waste sampling standards were applied. Finally, based on the results it can be concluded that increasing the number of increments for forming composite samples seems to have a larger beneficial effect on sampling quality than increasing the mass of the composite sample.

The obtained results show that the content of valuable plastics in MMW and MCW is about 15% in MMW and 15–23% in MCW. From a processing point of view, for the efficient recovery of these plastics, screening of the fine fraction after pre-shredding makes sense to remove contaminants and impurities. Additionally, after a material flow division based on particle dimensionality, further screening classification into targeted particle size classes is required to achieve higher concentrations of plastics and efficiently use plant capacities. Next, results presented show that all plastic types and mixtures investigated

are processable for production of flakes and granulates and finally can become a valuable secondary raw material after proper and quality focused treatment processes.

Regarding contaminants in the investigated waste, it can be concluded that they are not only enriched in specific materials, but also in selected particle size classes. Nevertheless, contaminants are present in a broad range of products and waste management needs to deal with them properly to produce quality assured secondary raw and energy materials from mixed waste for the recycling, recovery and co-processing sector.

Digitalization and Industry 4.0 approaches are at the very beginning of being introduced in the waste treatment sector. Especially, real-time (smart) monitoring, data analysis and management and process control for waste processing plants are to be developed in the future. The mixed waste treatment sector has specific challenges like the continuously changing waste quality as well as material and machine related fluctuations. These should be considered when developing smart treatment solutions. Finally, results gained within ReWaste4.0 support the development of further digitalized solutions for waste treatment sector and especially in case of a so-called smart waste factory.

ReWaste F—Recycling and Recovery of Waste for Future—is the logical high-quality R&D continuation for the period 2021 to 2025—building on extensive know-how and intensive results gained from ReWaste4.0, considering current and future waste streams (i.e., non-hazardous mixed waste), technology (machines, sensors, cameras) and digitalization (data analytics, simulation as well as intelligent material–machine–machine digital interconnection) developments.

ReWaste F has been developed with an enlarged consortium (i.e., four scientific and 14 company partners) and deepened data, sensor and digital interconnection expertise to create and implement a particle-, sensor- and data-based circular economy. In ReWaste F, partners will progress the branch towards a circular waste economy and technology according to the newly published European Green Deal 2019 for the sustainable and resource efficient development of the waste, secondary raw material and energy sectors. Furthermore, particle-, sensor- and data-based technologies (machines and processes become cyber–physical systems) and digital and intelligent interconnection (including the development of a manufacturer-independent “digital platform”) are crucial to enable the online/ontime communication of Material–Machine–Machine within new “Smart Waste Factory solutions” and to generate added value throughout the whole value chain.

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References

1. Austrian Research Promotion Agency (FFG). COMET—Competence Centers for Excellent Technologies—General Information, Factsheets and Success Stories. 2021. Available online: <https://www.ffg.at/en/comet-competence-centers-excellent-technologies> (accessed on 18 April 2021).
2. Sarc, R. ReWaste4.0—Recycling and Recovery of Waste 4.0. Application K-Project, Project Description, Version 1.1. 9 February 2017.
3. EC (European Commission). Closing the Loop: Commission Adopts Ambitious New Circular Economy Package to Boost Competitiveness, Create Jobs and Generate Sustainable Growth. 2015. Available online: http://europa.eu/rapid/press-release_IP-15-6203_en.htm (accessed on 1 March 2021).
4. EC (European Commission). Circular Economy Package. 2018. Available online: https://ec.europa.eu/environment/circular-economy/first_circular_economy_action_plan.html (accessed on 1 March 2021).
5. Sarc, R. ReWaste F—Recycling and Recovery of Waste for Future. Application Comet-Projects, Project Description, Version 1.0. 22 June 2020.

6. Pomberger, R.; Sarc, R.; Lorber, K.E. Dynamic visualisation of municipal waste management performance in the EU using Ternary Diagram method. *Waste Manag.* **2017**, *61*, 558–571. [CrossRef]
7. EC (European Commission). A European Green Deal. 2019. Available online: <https://ec.europa.eu/info/node/123797> (accessed on 1 March 2021).
8. Kaza, S.; Yao, L.C.; Bhada-Tata, P.; van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank: Washington, DC, USA, 2018.
9. Eurostat. Municipal Waste by Waste Management Operations, Last Updated: 16-02-2021. 2021. Available online: <http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do> (accessed on 1 March 2021).
10. Weißenbach, T.; Graf, J.; Pomberger, R.; Sarc, R. Calculation of the additional recycling potential in the European Union by implementing the Circular Economy Package. *Environ. Waste Manag. Recycl.* **2020**, *3*, 1–9.
11. Austrian Standard Institute (ASI). ÖNORM S 2100:2005 10 01, 2005. Abfallverzeichnis [Waste List].
12. BMU. Verordnung über die Bewirtschaftung von Gewerblichen Siedlungsabfällen und von Bestimmten Bau- und Abbruchabfällen (Gewerbeabfallverordnung) [Commercial Waste Ordinance]. Amendment 2017: BGBl. I S. 896. Available online: https://www.gesetze-im-internet.de/gewabfv_2017/BjNR089600017.html (accessed on 1 March 2021).
13. Weißenbach, T. Development of an Online/Onsite Method for the Characterization of Waste Streams in Waste Pre-Treatment Plants. Ph.D. Thesis, Montanuniversitaet Leoben, Leoben, Austria, 2021.
14. Weißenbach, T.; Pomberger, R.; Sarc, R. Composition of mixed commercial waste with focus on recyclable fractions. In Proceedings of the 7th International Conference on Sustainable Solid Waste Management, Heraklion, Greece, 26–29 June 2019.
15. Sarc, R.; Lorber, K.E. Production, quality and quality assurance of refuse derived fuels (RDFs). *Waste Manag.* **2013**, *33*, 1825–1834. [CrossRef] [PubMed]
16. Sarc, R.; Lorber, K.E.; Pomberger, R.; Rogetzer, M.; Sippl, E.M. Design, quality and quality assurance of solid recovered fuels (SRF) for the substitution of fossil feedstock in the cement industry. *Waste Manag. Res.* **2014**, *32*. [CrossRef]
17. Sarc, R.; Seidler, I.M.; Kandlbauer, L.; Lorber, K.E.; Pomberger, R. Design, quality and quality assurance of solid recovered fuels for the substitution of fossil feedstock in the cement industry—Update 2019. *Waste Manag. Res.* **2019**, *37*, 885–897. [CrossRef] [PubMed]
18. Sarc, R.; Kandlbauer, L.; Lorber, K.E.; Pomberger, R. Production and Characterisation of SRF Premium Quality from Municipal and Commercial Solid non-hazardous Wastes in Austria, Croatia, Slovenia and Slovakia. *Detritus* **2020**, *9*, 125–137. [CrossRef]
19. BKA (Bundeskanzleramt Österreich). Bundesgesetz über eine Nachhaltige Abfallwirtschaft (Abfallwirtschaftsgesetz 2002—AWG 2002) [Waste Management Act]. BGBl. I Nr. 102/2002, as Amended BGBl. I Nr. 24/2020. Available online: <https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20002086> (accessed on 1 March 2021).
20. Möllnitz, S.; Khodier, K.; Pomberger, R.; Sarc, R. Grain size dependent distribution of different plastic types in coarse shredded mixed commercial and municipal waste. *Waste Manag.* **2020**, *103*, 388–398. [CrossRef]
21. BMK. *Die Bestandsaufnahme der Abfallwirtschaft in Österreich, Statusbericht 2020 (Referenzjahr 2018)* [Inventory of Waste Management in Austria, Status Report 2020 (Reference Year 2018)]; Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology: Vienna, Austria, 2020.
22. European Commission. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions a European Strategy for Plastics in a Circular Economy (SWD (2018) 16 Final). 2018. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN> (accessed on 1 March 2021).
23. Tschandl, M.; Peßl, E.; Sorko, S.; Lenart, K. Roadmap Industrie 4.0 für Unternehmen aus dem Umwelt- bzw. Abfallbereich (Roadmap industry 4.0 for companies in the environmental and waste management sector). 2019.
24. Curtis, A.; Sarc, R. Definition of the Term “Smart Waste Factory Network” within the Project ReWaste4.0, Montanuniversitaet Leoben on 8 October 2018.
25. Sarc, R.; Curtis, A.; Kandlbauer, L.; Khodier, K.; Lorber, K.E.; Pomberger, R. Digitalisation and Intelligent Robotics in Value Chain of Circular Economy Oriented Waste Management—A Review. *Waste Manag.* **2019**, *95*, 476–492. [CrossRef] [PubMed]
26. Green Tech Cluster. Digitale Abfallwirtschaft—Mehrwert Entlang der Gesamten Wertschöpfungskette (Digital Waste Management—Added Value along the Entire Value Chain). 2018. Available online: www.greentech.at (accessed on 1 March 2021).
27. Abdallah, M.; Abu Talib, M.; Feroz, S.; Nasir, Q.; Abdalla, H.; Mahfood, B. Artificial intelligence applications in solid waste management: A systematic research review. *Waste Manag.* **2020**, *109*, 231–246. [CrossRef]
28. ASI (Austrian Standards Institute). ÖNORM EN 15442—Solid Recovered Fuels—Methods for Sampling; ASI: Vienna, Austria, 2011.
29. Viczek, S. Origins, Distribution, and Fate of Contaminants and Ash Constituents in Waste for SRF Production and Co-Processing. Ph.D. Thesis, Montanuniversitaet Leoben, Leoben, Austria, 2021.
30. Khodier, K.; Viczek, S.A.; Curtis, A.; Aldrian, A.; O’Leary, P.; Lehner, M.; Sarc, R. Sampling and Analysis of Coarsely Shredded Mixed Commercial Waste. Part I: Procedure, Particle Size and Sorting Analysis. *Int. J. Environ. Sci. Technol.* **2019**, *17*, 959–972. [CrossRef]
31. Viczek, S.A.; Kandlbauer, L.; Khodier, K.; Aldrian, A.; Sarc, R. Sampling and analysis of coarsely shredded mixed commercial waste. Part II: Particle size-dependent element determination. *Int. J. Environ. Sci. Technol.* **2021**, under review.
32. Khodier, K. Empirical Modelling for the Optimized Operation and Real-Time Control of Coarse Shredders for Mixed Commercial Waste. Ph.D. Thesis, Montanuniversitaet Leoben, Leoben, Austria, 2021.

33. European Union (EU). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008; Waste and Repealing Certain Directives*: Brussels, Belgium, 2008.
34. BMLFUW. Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft und des Bundesministers für Wirtschaft, Familie und Jugend über die Verbrennung von Abfällen (Abfallverbrennungsverordnung—AVV) [Waste Incineration Ordinance] BGBl. II Nr. 389/2002, as Amended BGBl. II Nr. 135/2013. Available online: <https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20002239> (accessed on 1 March 2021).
35. Lorber, K.E.; Sarc, R.; Aldrian, A. Design and quality assurance for solid recovered fuel. *Waste Manag. Res.* **2012**, *30*, 370–380. [CrossRef]
36. Viczek, S.A.; Aldrian, A.; Pomberger, R.; Sarc, R. Origins and carriers of Sb, As, Cd, Cl, Cr, Co, Pb, Hg, and Ni in mixed solid waste—A literature-based evaluation. *Waste Manag.* **2020**, *103*, 87–112. [CrossRef] [PubMed]
37. Viczek, S.A.; Khodier, K.; Kandlbauer, L.; Aldrian, A.; Redhammer, G.; Tippelt, G.; Sarc, R. The particle size-dependent distribution of chemical elements in mixed commercial waste and implications for enhancing SRF quality. *Sci. Total Environ.* **2021**, *776*, 145343. [CrossRef]
38. Curtis, A.; Adam, J.; Pomberger, R.; Sarc, R. Grain size-related Characterization of Various Non-hazardous Municipal and Commercial Waste for Solid Recovered Fuel (SRF) Production. *Detritus* **2019**, *7*, 55–67. [CrossRef]
39. Viczek, S.A.; Lorber, K.E.; Pomberger, R.; Sarc, R. Production of contaminant-depleted solid recovered fuel from mixed commercial waste. *Fuel* **2021**, *294*, 120414. [CrossRef]
40. Viczek, S.A.; Sarc, R.; Pomberger, R. *Grain Size Dependent Distribution of Contaminants in Coarse-Shredded Commercial Waste*; Thiel, S., Thomé-Kozmiensky, E., Winter, F., Juchelková, D., Eds.; IRRC, Waste Management: Neuruppin, Germany, 2019; ISBN 978-3-944310-48-0.
41. Khodier, K.; Feyerer, C.; Möllnitz, S.; Curtis, A.; Sarc, R. Efficient derivation of significant results from mechanical processing experiments with mixed solid waste: Coarse-shredding of commercial waste. *Waste Manag.* **2020**, *121*, 164–174. [CrossRef]
42. Möllnitz, S.; Küppers, B.; Curtis, A.; Khodier, K.; Sarc, R. Influence of Pre-Screening on Down-Stream Processing for the Production of Plastic Enriched Fractions for Recycling from Mixed Commercial and Municipal Waste. *Waste Manag.* **2020**, *119*, 365–373. [CrossRef] [PubMed]
43. Letcher, T.M. *Plastic Waste and Recycling—Environmental Impact, Societal Issues, Prevention, and Solutions*; Elsevier: London, UK, 2020.
44. Friedrich, K.; Möllnitz, S.; Holzschuster, S.; Pomberger, R.; Vollprecht, D.; Sarc, R. Benchmark Analysis for Plastic Recyclates in Austrian Waste Management. *Detritus* **2020**, *9*, 105–112. [CrossRef]
45. Möllnitz, S.; Feuchter, M.; Duretek, I.; Schmidt, G.; Sarc, R. Verification of the processability of different polymer fractions recovered from mixed wastes and determination of material properties. *Polym. Recycl. Spec. Issue Polym. Waste Recycl. Manag.* **2021**, *13*, 457. [CrossRef]
46. Möllnitz, S.; Bauer, M.; Schwabel, D.; Schmidt, G.; Sarc, R. Wet-mechanical processing of plastic-rich 2D-fractions from mixed wastes for recycling purposes. *Waste Manag. Res.* **2021**, 1–13. [CrossRef]
47. Bauer, M.; Lehner, M.; Schwabl, D.; Flachberger, H.; Kranzinger, L.; Pomberger, R.; Hofer, W. Sink–float density separation of post-consumer plastics for feedstock recycling. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 1781–1791. [CrossRef]
48. Bauer, M.; Lehner, M. Post-consumer plastics in Austria and their potential for chemical recycling. In Proceedings of the ISWA World Congress 2013 Vienna, Vienna, Austria, 7–11 October 2013; International Solid Waste Association: Vienna, Austria, 2013.
49. CEN. *CENprEN 15359:2010 Solid Recovered Fuels—Specifications and Classes*; CEN: Brussels, Belgium, 2010.
50. BMLFUW. *Richtlinie für Ersatzbrennstoffe [Guideline for Waste Fuels]*; BMLFUW: Vienna, Austria, 2008.
51. Sarc, R. Herstellung, Qualität und Qualitätssicherung von Ersatzbrennstoffen zur Erreichung der 100%-Igen Thermischen Substitution in der Zementindustrie [Design, Quality and Quality Assurance of Solid Recovered Fuel (SRF) for Achieving 100% Thermal Substitution in Cement Industry]. Ph.D. Thesis, Montanuniversität Leoben, Leoben, Austria, 2015.
52. GCCA (Global Cement and Concrete Association). Getting the Numbers Right. 2020. Available online: https://gccassociation.org/gnr/Excel/GNR%20-%20Totals_&_Averages%20-%20Light%20Report%202018.xls (accessed on 1 March 2021).
53. Viczek, S.A.; Aldrian, A.; Pomberger, R.; Sarc, R. Determination of the material-recyclable share of SRF during co-processing in the cement industry. *Resour. Conserv. Recycl.* **2020**, *156*, 104696. [CrossRef]
54. Hökfors, B.; Boström, D.; Viggh, E.; Backman, R. On the phase chemistry of Portland cement clinker. *Adv. Cement Res.* **2015**, *27*, 50–60. [CrossRef]
55. Aldrian, A.; Viczek, S.A.; Pomberger, R.; Sarc, R. Methods for identifying the material-recyclable share of SRF during co-processing in the cement industry. *Methods X* **2020**, *7*, 100837. [CrossRef]
56. Viczek, S.A.; Aldrian, A.; Pomberger, R.; Sarc, R. Origins of mineral constituents in SRF and implications for recycling during co-processing in the cement industry. *Waste Manag.* **2021**, *126*, 423–432. [CrossRef]
57. Sarc, R.; Hermann, R. *Unternehmensbefragung zum Thema Abfallwirtschaft 4.0 [Company Survey to the Topic Waste Management 4.0]*; Pomberger, R., Adam, J., Aldrian, A., Curtis, A., Friedrich, K., Kranzinger, L., Küppers, B., Lorber, K.E., Möllnitz, S., Neuhold, S., et al., Eds.; Recy&DepoTech: Leoben, Austria, 2018.
58. Khodier, K.; Sarc, R. Distribution-independent empirical modeling of particle size distributions—Coarse-shredding of mixed commercial waste. *Processes* **2021**, *9*, 414. [CrossRef]

-
59. Kandlbauer, L.; Khodier, K.; Ninevski, D.; Sarc, R. Sensor-based Particle Size Determination of Shredded Mixed Commercial Waste based on two-dimensional Images. *Waste Manag.* **2021**, *120*, 784–794. [[CrossRef](#)] [[PubMed](#)]
 60. Weißenbach, T.; Sarc, R. Investigation of particle-specific characteristics of non-hazardous, fine shredded mixed waste. *Waste Manag.* **2021**, *119*, 162–171. [[CrossRef](#)]
 61. Pomberger, R.; Küppers, B. Entwicklungen in der Sensorgestützten Sortiertechnik [Developments in Sensor-Based Sorting Technology]. In Proceedings of the Österreichische Abfallwirtschaftstagung 2017—Die Digitalisierung der Abfallwirtschaft, Graz, Austria, 10–11 May 2017.
 62. Flamme, S.; Hams, S.; Zorn, M. *Sensortechnologien in der Kreislaufwirtschaft [Sensor Technologies in the Recycling Economy]*; Pomberger, R., Adam, J., Aldrian, A., Curtis, A., Friedrich, K., Kranzinger, L., Küppers, B., Lorber, K.E., Möllnitz, S., Neuhold, S., et al., Eds.; Recy&DepoTech: Leoben, Austria, 2018.
 63. Weißenbach, T.; Sarc, R. Investigation of particle-specific characteristics of coarse-shredded waste. *Waste Manag.* **2021**, *119*, 162–171. [[CrossRef](#)] [[PubMed](#)]
 64. Curtis, A.; Küppers, B.; Möllnitz, S.; Khodier, K.; Sarc, R. Real time material flow monitoring in mechanical waste processing and the relevance of fluctuations. *Waste Manag.* **2021**, *120*, 687–697. [[CrossRef](#)] [[PubMed](#)]
 65. Curtis, A.; Sarc, R. Real-Time Monitoring of Volume Flow, Mass Flow and Shredder Power Consumption in Mixed Solid Waste Processing. *Waste Manag.* **2021**, under review.