Sustainability of Waste Management System: Treatment and Separation for Material Recovery

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Sustainability of Waste Management System - Treatment and Separation for Material Recovery

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1. Definition/description

Increased global concern on the state of our climate has driven also the waste management sector to look for solutions that enable lowering of the environmental impacts by increasing waste reduction and material recycling. Material recycling is more feasible and efficient when there is source separation in place because source separation usually leads to the best quality of the separated materials. However, sometimes source separation does not work properly (e.g. because of the low education level of people) or it is difficult to apply (e.g. because of a fixed and dense city infrastructure). The strict material recycling targets in the EU necessity that mechanical separation is included as a tool for increasing the recycling rate. The aim of the mechanical treatment is to separate materials suitable for recycling from the mixed waste stream by separating recoverable components and impurities to different streams. A multitude of processes is usually required to obtain recyclable materials out of the mixed waste stream, for example from mixed municipal solid waste (MSW) or mixed construction and demolition waste (C&D waste). However, it should be borne in mind that often the most important factors from the environmental impacts point of view for recovery of materials by mechanical treatment are yield of recoverables, quality and demand of recovered materials as well as the environmental impact of replaced virgin materials. At the end of the day, the tightened recycling rates strive for the development of various treatment and separation technologies and their better performance is achieved.

2. Synonyms

Mechanical treatment, separation technologies

3. Introduction

Increased global concern on the state of our climate has driven the waste management sector to look for technical solutions that enable the lowering of the environmental impacts. The goal, especially in the EU, has been to firstly reduce the waste generation as much as possible. This is achieved by striving to design products and services according to the circular economy concept that support the goal of waste reduction as well as the efficient recycling at the end of life (EoL) of the product. Only as a last resort should there be a safe disposal of waste.

Legislation lays down the definitions and regulations guiding the development also in waste management sector. In EU-28, the overarching legislation is provided by the waste framework directive (2008/98/EC). Waste framework directive, among other legislative acts, provides the basis for measures to be taken in waste management with the waste hierarchy stating as the preferred approach to be waste reduction and after that recycling.

The source separation of waste is the most efficient way to get waste materials suitable for recycling. Source separation is never perfect because there are always people who are not willing or able to do the separation work. Although there are impurities in the source separated fractions, they have a higher share of desired materials than the outputs of mechanical treatment. However, source separation is not possible in some cases due to various reasons and efficient mechanical treatment is needed to obtain waste fractions for recycling and to complete the separation of different materials out of the mixed stream in order to facilitate the increase in the recycling rate.

The tightening goals for recycling rates are justified by the anticipated lower environmental impacts from waste management. Often, the separation and pre-treatment processes themselves, do not make very large impacts compared to the impacts of utilization or avoidance of landfilling. For example, when it is possible to improve the fuel properties of waste to reduce the auxiliary coal need the environmental benefits are evident (Havukainen et al., 2017). In some cases, however, if disposal of the waste material would not cause large environmental impacts and if recovery of it either does not replace environmentally intensive materials, the mechanical treatment phases can make a large contribution to the whole life cycle impacts (Deviatkin, 2017). In such a case, it is possible that treatment causes more environmental impacts than can be achieved benefits with the recovery of that material.

This chapter of the Encyclopedia focuses on the mechanical treatment and separation of usable materials from mixed waste streams. The basic principles of mechanical treatment, as well as the treatment processes, are presented. Besides, mechanical treatment of waste to produce solid recovered (SRF), preparation from waste, and mechanical separation of plastic waste, are discussed in more detail.

4. Technologies

The aim of the mechanical treatment is to separate materials suitable for recycling from the mixed waste stream by separating recoverable components and impurities to different streams (Gundupalli et al., 2017). A multitude of processes is usually required to obtain recyclable material out of the mixed waste streams, for example from mixed MSW or mixed C&D waste. The first step usually is size reduction to separate entangled materials from each other, as well as reduce the particle size, thus facilitating the efficient separation of materials in subsequent processes. The following material separation can include separation based on particle size, density-based separation, magnetic separation, etc. Figure 1 presents a simplified chart with the possible treatment phases and suitable technologies or devices which can be used in the different treatment phases.

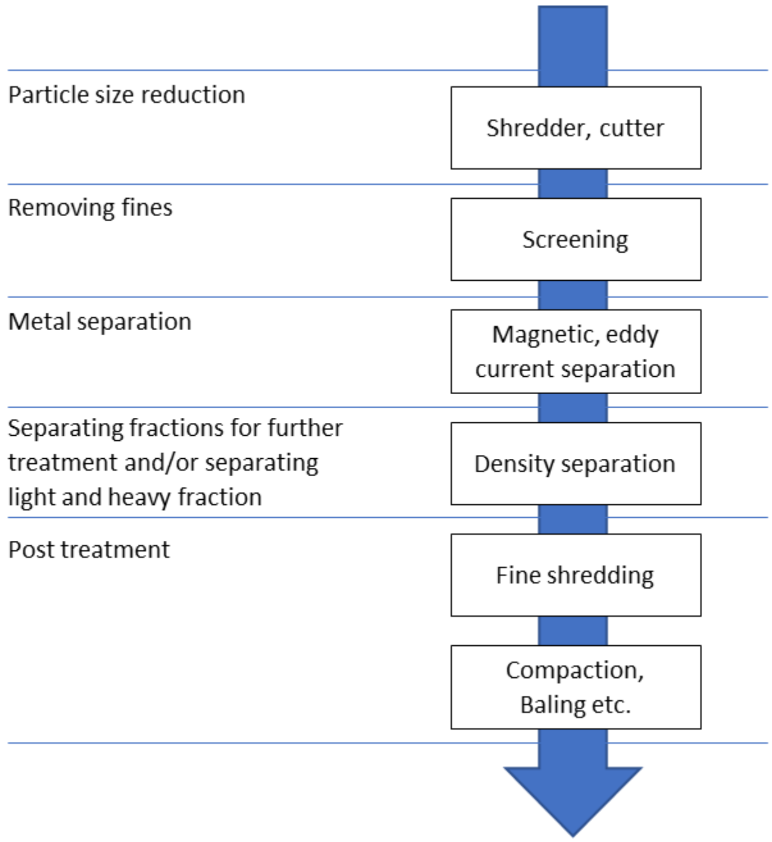

Figure 1. Simplified chart of possible waste separation steps and possible technologies or devices suitable for the separation step.

The mechanical processes are not recovering 100% of the desired material from the mixed waste neither they produce 100% pure fractions of the separation which means that the efficiency of the processes is never ideal. The purity rate, the recovery degree, and the overall efficiency are used to describe the efficacy of the separation processes to perform separation of desired fractions from the reject fractions.

Figure 2 presents a simplified flowchart of mass flows of a separation process. These mass flows can be used to calculate the purity degree, the recovery degree, as well as the efficiency of the separation.

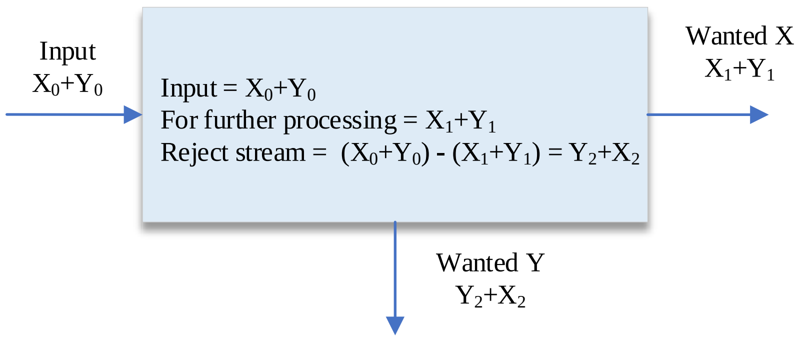

Figure 2. Simplified flowchart of separation mass flows.

There are almost always some impurities in the fraction which has been separated for the recovery purposes. For example, when separating metals from a mixed flow, the separated metal fraction can include, e.g. wood fixed in the demolished nails or plastic coverings of metallic pipes. The purity degree (P) can be used to calculate the recoverable percentage of material from separated total mass flow (for example from underflow).

$$P_{X1} = \frac{X_1}{X_1+Y_1} 100\% \quad (1)$$

, where

X_1 = mass of wanted material to be separated

Y_1 = mass of other material unintentionally separated from the input mass

The recovery degree (R) shows the percentage of the separated recoverable material from the input recoverable material.

$$R_{X1} = \frac{X_1}{X_0} 100\% \quad (2)$$

, where

X_O = mass of wanted material in the input stream

The efficiency (E) combines both purity and recovery degree and provides an overall efficiency of a given separation technology.

$$E = \left|\frac{X_1}{X_0} - \frac{Y_1}{Y_0}\right| 100\% \quad (3)$$

, where

Y_0 = mass of other material in the input stream

There is a wide range of recovery efficiencies for the separation technologies, which can be seen from Table 1.

Table 1. Material recovery efficiencies of selected separation technologies (McDougall and White, 2001).

Technology	Separating	Efficiency (%)
Magnet separator	Ferrous metal	60-90
Eddy current separator	Non-ferrous metal	60-90
Disc screen	Particulates	50-90
Trommel screen	Particulates	80-90
Vibrating screen	Particulates	60-90
Air classifier	Heavy and light fraction	60-90

4.1. Particle size reduction

Particle size reduction is needed to reduce the particle size and to some extent, help separate the entangled materials from each other. The main aim is to enable the separation of materials from each other in the subsequent processes. (McDougall and White, 2001) After the treatment, the material has more homogenous particle size distribution while the bulk density is not necessarily changing. Commonly used equipment includes hammermills, impact crushers, cutters, cascade mills and jaw crushers. The factors that affect crusher selection include (Tchobanoglous et al., 1993):

- Properties of the material to be processed
- Feeding method of the crusher
- Criteria for the produced particle size distribution
- Desired properties of the processed material
- Desired usage of the processed material
- Equipment placement circumstances
- Transport and storage circumstances of the crushed material.

Hammermills are commonly used for crushing EoL vehicles (ELVs), C&D waste, especially if C&D waste contains concrete, bricks and other hard inert materials, as well as commercial and industrial waste (C&I waste). Hammermill consists of metal bars or plates that act as hammers which are mounted on a horizontal or a vertical shaft. The hammers hack the material against a crushing wall with a rotational speed of 700–1200 rpm. Increasing the number of hammers enables the production of small particle size while causing a reduction of the feeding rate (Christensen, 2010). There is a grate with a certain size of slots, through which the crushed particles drop out from the hammer mill. The size of the slots determines the maximum particle size coming out from the mill. Flail mills are like hammermills, but the material is not forced through a grate and hammers are further from each other. The processed material from hammermill and flail mill has heterogeneous particle size distribution, while hammermill has smaller output particle size distribution. It is also possible to use shredder which has for example teeth attached on one shaft providing a robust shredding of for example C&D waste as in Figure 3.

Cutting shredders are based on the rotating and intersecting blades that are placed between each other on a shaft with a rotational speed of approximately 60–190 rpm and an option for changing the rotation direction. These can be used for different kinds of waste but especially for stretchy and high-tensile materials as well as bag rippers. Shredders are often used for size reduction of MSW and to some extent also to C&D waste if it is mostly containing wood, plastic, and cardboard.

Figure 3. Mobile Terminator 5000S crusher crushing mixed C&D waste © Havukainen

4.2. Screening

During the screening process, the incoming material is separated into two or more categories based on the particle size. As a basis for design the following characteristics are used: the desired mass flow of the incoming material, separation capacity per screen area and delay time of the screening. Screens can be used for the following purposes (Tchobanoglous et al., 1993):

- Removal of too big particles and pieces
- Removal of too small particles
- Sorting into light combustible and heavy incombustible fractions
- Separation of paper, plastic and other light fractions from glass and metal
- Separation of glass, gravel and sand from combustibles
- Separation of rocks and other large pieces from soil ingredients
- Separating big particles from ash
- Quality improvement of handled final product (for example compost)

Various types of screening devices include trommel screens, vibrating screens Figure 4, and disc screens. Rotating trommel screen has been used in several applications for waste material screening and can be used as a primary screening or final screening method. The material is tumbling in the trommel until it finds a suitable opening on the screen or it comes from the other end of the trommel. The sizes of the openings in the trommel, rotating speed, inclination all affect the trommel the throughput and efficiency of the trommel.

Figure 4. Mobile Keestrack screen separating crushed mixed C&D waste: a = fine underflow, b = magnetic fraction, c = energy waste with other material continuing to air classifier. © Havukainen.

4.3. Density separation

Density separation utilizes the different densities and aerodynamic properties of the materials in the separation process based on a gas flow or liquid. Air separation is based on the idea that with a certain velocity of the air it is possible to float certain pieces. The required velocity is dependent on the density, form, and size of the particles. Air classifier is the most commonly used and simplest technology for density separation. Waste is dropped from the top of a chute while air is introduced from the bottom. The air can float certain particles but not heavy particles, which enables separating the light fraction from heavy fraction Figure 5. This technology is used for example after crushing the ELVs to separate a heavy fraction and light fraction (also called fluff). Density separation can also be based on using liquids that have different densities to enable the sinking or floating of the materials. This requires specific kinds of liquids whose density can be changed. Sinking/floating devices can be used for example separating light metals.

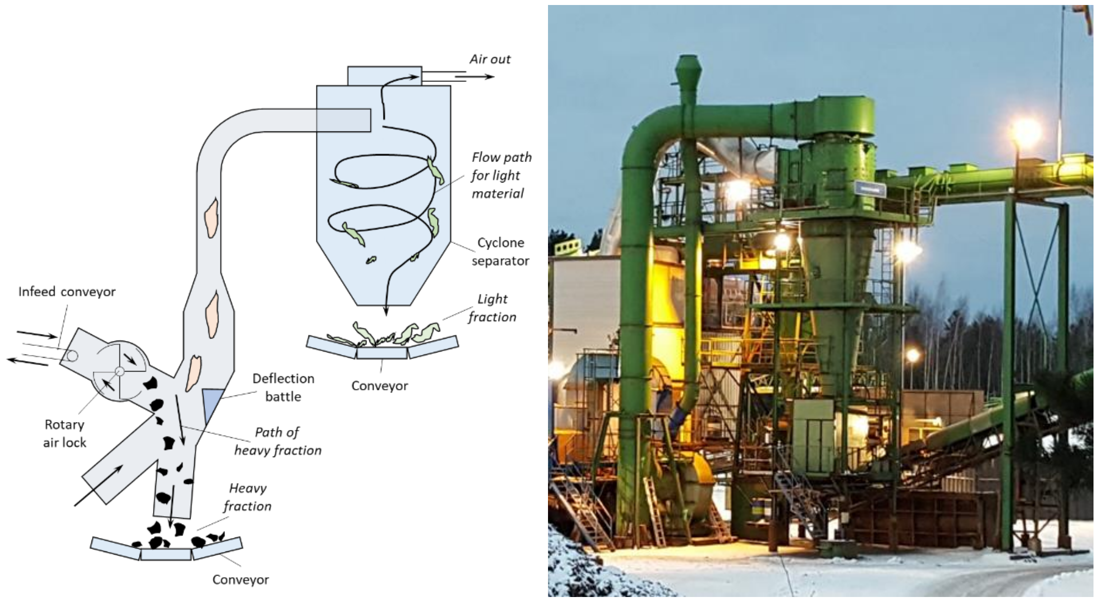

Figure 5. Operating principle of an air classifier (left, modified from Thorton, 2019) and air classifier separating fluff after ELVs crushing (right, © Havukainen)

A Ballistic separator is utilizing various properties of the waste namely particle size, density, and rigidness (Christensen, 2010). It can be used to separate heavy particles out of the light materials and can be placed for example after trommel screen to separate heavy and light fractions. It usually consists of a vibrating inclined deck which has openings in it to allow fluidizing air to pass through it. The deck is vibrating in downwards or upwards direction. The heavy fraction moves with the movement of vibrations. The light fraction is moving to the opposite direction because of the heavy reorganization of the waste on the deck as well as vibration deck vibration and fluidizing air. A third fraction is formed from the material which is falling through the openings in the deck (Figure 6).

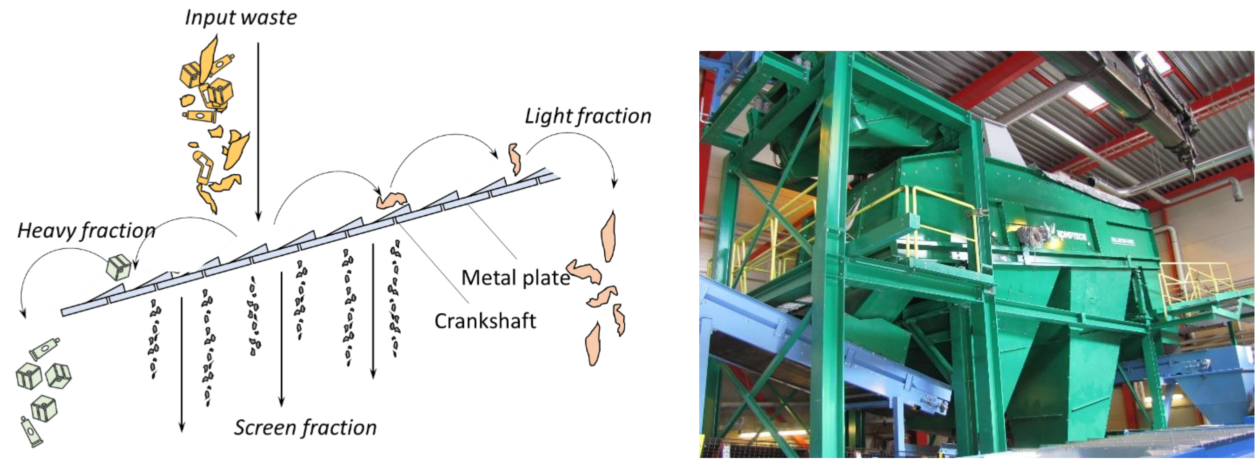

Figure 6. Operating principle of a ballistic separator (left modified from Tinsley, 2019) and Ballistor 6400 (right © Lauri Rahikainen, Vimelco).

4.4. Magnetic separation

Magnetic separation is used to separate pieces of ferrous metals from the waste stream by utilizing the magnetic field. The magnetic separation can use either permanent or electrical magnets and the efficiency of the separation can be over 95%. The system usually involves an overhead magnet with belt conveyer which conveys the material. To ensure effective separation of the ferrous metals, there usually has to be size reduction before magnetic separation. In Figure 7, the magnetic separation is situated after crushing and screening devices on top of the conveyer taking the screened material to the next treatment phase.

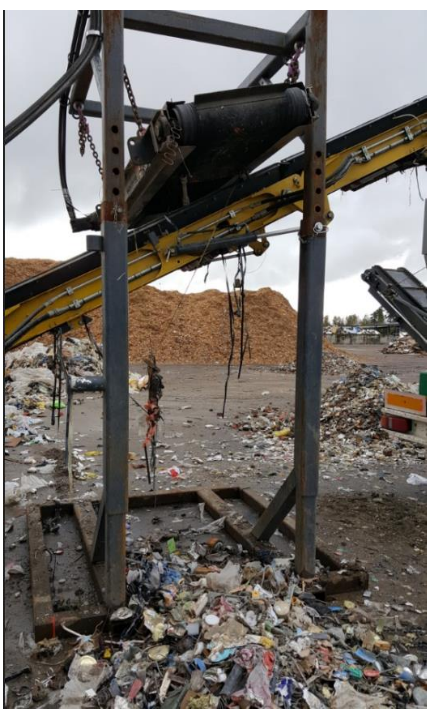

Figure 7. A magnetic separator over the conveying belt of the Keestrack mobile screen and separated magnetic fraction on the ground. © Havukainen

4.5. Eddy current separation

Eddy current separation is a process where a voltage is formed to a conductive piece placed in the variable magnetic field. This voltage causes an electric current to the piece which induces an electrical field in turn that is polarized opposite to the variable magnetic field. The created opposite polarization causes a repulsive force between the magnetic field and the conductive piece. (McDougall and White, 2001) With this method, the conductive pieces can be removed from the other material flow. Alternating current or permanent magnets with different poles can be used to produce the variable magnetic field, Figure 8. In addition to magnetic separation, eddy current separation is widely used. The purity and recovery degree can be even 98%.

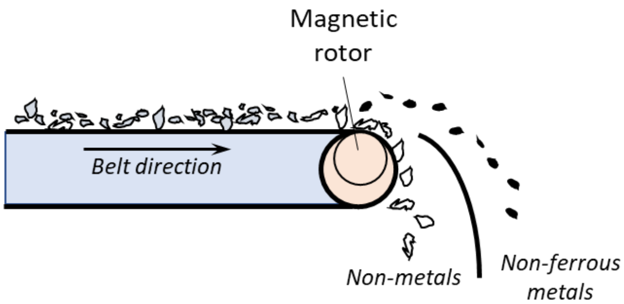

Figure 8. Principle of eddy current separation (modified from Magnapower Equipment Ltd., 2019).

4.6. Optical sorting

Optical sorting is used to separate different materials from the waste by utilizing optical identification. The color of the material is often used as an optical identifier. The method can be used for relatively large particles with particle size over 20 cm when treating for example MSW. One application is to distinguish different color waste bags from each other for example when one color is used for mixed waste and another for energy waste. Optical sorting can also be used for significantly smaller particle size for example when separating copper from other metals. The copper parts are removed by an air blow by engineered air blowing from a gap between conveyors to the conveyor below. NIR (near-infrared) separation technologies utilize optical detection on the NIR wavelength region light (700–1200 nm), which allows for better penetration of the detection reducing the problems related to the impurities (Figure 9). NIR technology is widely used in optical sorting because it enables the detection of plastic grades, as well as different fibers such as paper, cardboard, and wood. Optical sorting can achieve high sorting efficiencies. For example, Koyanaka and Kobayashi (2010) reported a sorting efficiency of 85% for non-ferrous metals with a multivariate analysis based optical sorting technology including 3D shape detection camera and a weight-meter.

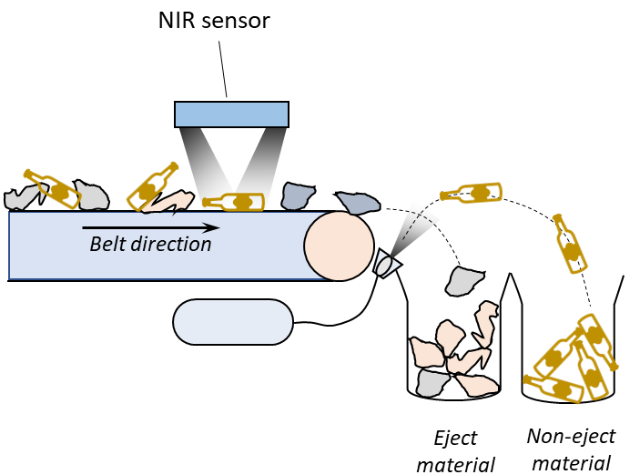

Figure 9. Illustration of the principle of an optical sorting technology (modified from EMS Turnkey Waste Recycling Solutions, 2012).

4.7. Compaction

The purpose of compaction is to reduce the volume requirement of material to facilitate efficient storing and transportation. Technologies usable for compaction include baling, cubing, pelletizing and briquette production. Baling can be used for reducing volume requirement of material for transport or storage purposes of recovered material whereas cubing, pelletizing or briquet production are sometimes used to produce densified refuse-derived fuel (RDF) or SRF. Increased costs of treatment are weighed against the transportation costs and for longer transportation distances the treatment can be justified. The performance of compaction is characterized by compaction ratio and volume reduction. Compaction ratio is the ratio of the initial volume and compacted volume whereas volume reduction is the ratio of reduced volume by compaction and the initial volume (Tchobanoglous et al., 1993).

The characteristics that need to be considered in the selection of compaction equipment include purposes for the densification, desired throughput of the material, moisture content, specific weight of the input material, available handling equipment before and after compaction as well as site-specific constraints such as available floor area and height of the space for the equipment. Another consideration is that the compacted bales, cubes, pellets or briquets require some cover from rain even though some materials might endure moisture. One alternative for a cover for bales is to wrap them after compaction to protect them against moisture as illustrated in Figure 10.

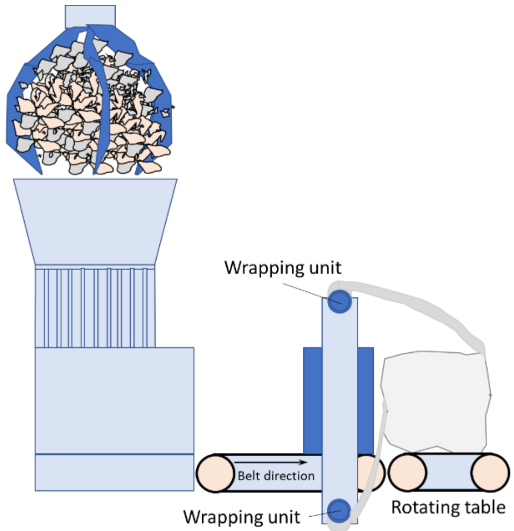

Figure 10. Illustration of the principle of direct wrapping from a bale chamber (modified from Cross wrap Ltd., 2019).

4.8. Robotic separator

The development of industrial robots, artificial intelligence as well as material analyzing sensors have enabled the development of indirect sorting by automatic sorting lines. Indirect sorting means that sensors detect the materials and robots can be used to extract the detected materials from a waste stream (Gundupalli et al., 2017). The robots allow the sorting to take place the whole week around the clock as opposed to manual picking. The utilized sensors can be selected based on the desired separated fractions such as laser-induced breakdown spectroscopy (LIBS), X-ray detection, NIR sensor, visual light spectrum (VIS) sensor. LIBS and XRF can be used for detecting metals, different plastic qualities or wood quality. Cameras and image recognition can be also used.

Applying a set of sensors can provide a wider range of materials to be detected and in combination with artificial intelligence a possibility for autonomous decision making and learning of robots based on the analysis results, Figure 11. The robotic sorting line can be used for example for detecting and extracting materials from pre-sorted MSW, C&I waste, C&D plastics, waste packages, and scrap metal.

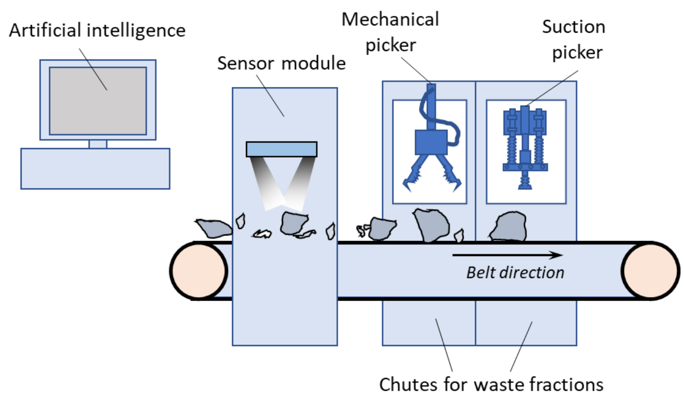

Figure 11. Illustration of the principle of the waste separation process utilizing robots (modified from ZenRobotics, 2019).

5. Separation and treatment lines

5.1. SRF production

The aim of the SRF production line is to produce a more homogenous fuel and increase material recycling. The treatment line with crushing, screening and various other separation devices provides an end-product with more homogenous heating value compared to the untreated waste. The resulting smaller particle size distribution lowers the requirements for conveyors and feed devices. The treatment process enables the removal of harmful substances which results in lower emissions and cheaper flue gas treatment systems. In addition, the removal of harmful substance reduces the corrosivity and fouling in the subsequent combustion processes. Another benefit of the SRF production lines is to separate recyclable fractions of the waste streams, such as ferrous and non-ferrous metals. According to Wilén (2004), the benefits of producing SRF from the waste include the possibility of utilizing the SRF in fluidized bed combustion or gasification with a possibility for higher steam values and subsequent higher power production efficiency.

In the SRF treatment process, such as in Figure 12, waste is first fed into a size reduction device to provide a smaller particle size for subsequent separation processes. following treatment processes can include a magnetic and eddy current separation separating ferrous and non-ferrous metal fractions for material recycling. A fine screen can then be used for removal of the fine fraction containing most of the organic waste, sand, and glass. This fine fraction removal can also be achieved with for example a trommel screen or ballistic separator. Fine fraction removal decreases the moisture content of waste since part of the moist organic fraction is removed. The resulting fine fraction contains mainly organic waste and can be directed to an anaerobic digestion or composting process, but the end-product from these processes is contaminated by the impurities ending up to the fine fraction, thus requiring further removal of these impurities. After the removal of metals and fine fraction, the waste can be directed to a density separation process, for example, air classifier, whose main aim is to separate light fraction and heavy fraction. The heavy fraction contains heavy waste fractions such as stones as well as remaining glass and organics. The resulting light fraction can be used as SRF or it can be directed to the additional size reduction process. Figure 13 depicts how the SRF production line can be compactly assembled at site.

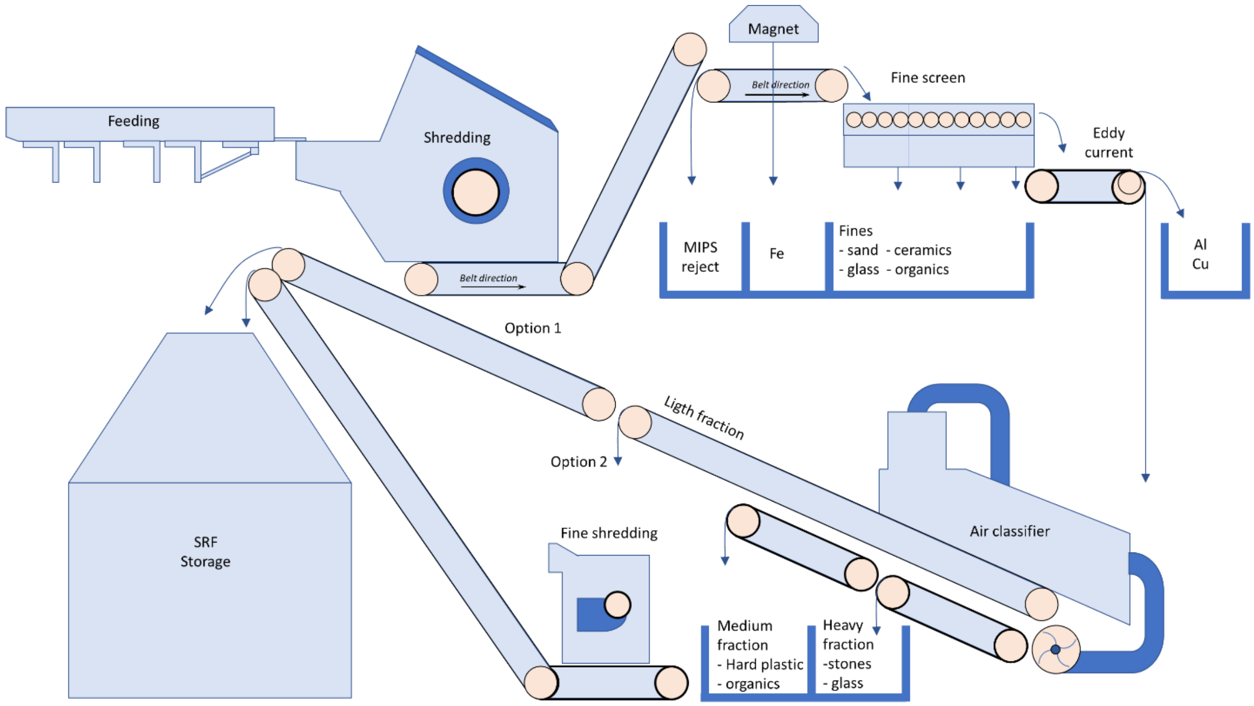

Figure 12. Illustrative treatment line for SRF production (MIPS = massive impact protection) (modified from Kuusinen, 2016)

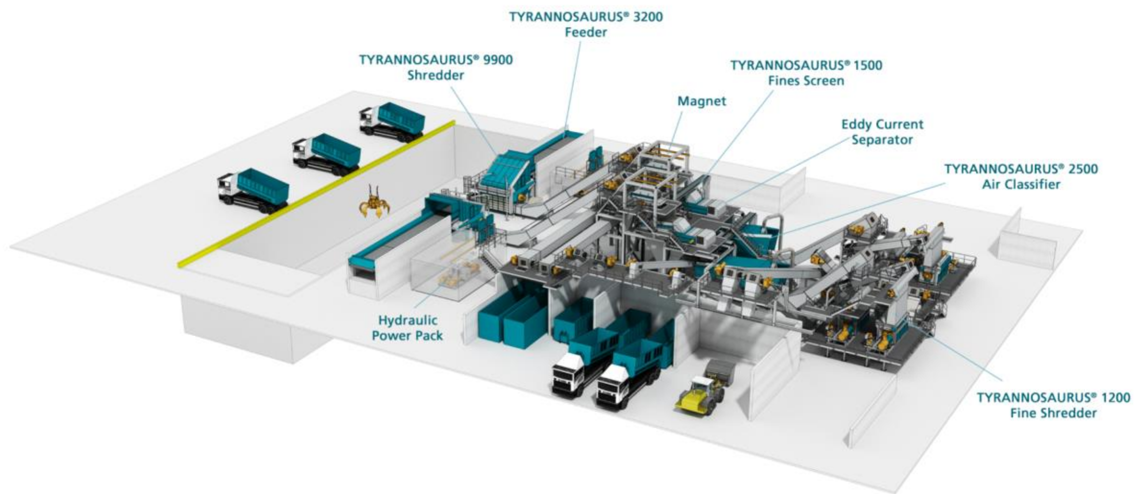

Figure 13. SRF production line (courtesy of BMH).

5.2. Plastic waste separation

Mechanical treatment processes can be used to separate different plastic qualities from a source-separated mixed plastic waste. For example, in Finland, there is source separation of mixed plastic packaging organized according to the extended producer responsibility system. This mixed plastic packaging waste is directed to a plastic separation system that can then separate the different plastic polymers. For example, in the plastics treatment plant of Fortum Waste Solutions Ltd, the source-separated plastic packaging waste is separated into LDPE, HDPE, PP, mixed plastic fraction, as well as the fraction going for SRF production.

LDPE, HDPE, and PP are granulated to be used in the plastics industry and mixed plastic is utilized in mixed plastic products such as profiles. According to Kampmann (2019), the outputs from plastic separation can include PET bottles, HDPE bottles, mixed plastics, PET, HDPE, PP or PS depending on the sorting scheme, source-separation efficiency, and mechanical treatment efficiency.

Plastic waste separation can start with a ballistic separator which would separate 2D and 3D plastic waste from each other to different lines. The 3D plastic has distinguishable greater thickness compared to 2D plastics. The following separation line utilizing optical sorting with NIR technology can then be utilized to detect and subsequently separate desired plastic qualities. The 2D fraction can include for example films composed of LDPE and the 3D fraction plastic grades HDPE, PP, and PET. Both fractions will also include materials that can be further directed to mixed plastic fraction or to SRF production. After the separation of the plastic fractions the sorted plastic fractions can be directed to the subsequent washing system. This can include shredding, different processes for the washing and drying process. Subsequently, the dried plastic fractions can then be directed to granulation and the ready granulates can be used in the plastics industry, Figure 14. This kind of separation line has difficulties with separating black plastics since NIR technology is not able to detect it (Kampmann, 2019). One possibility could be to install a hyperspectral camera such as Specim FX50 to detect black plastics (Specim, 2019).

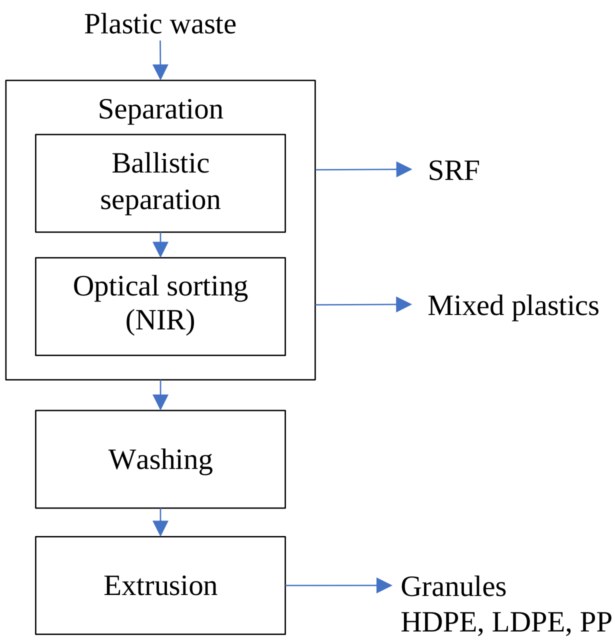

Figure 14. Illustrative flow chart of a possible line for plastic waste separation (modified from Koivuniemi, 2019)

6. Summary

Material recycling is more feasible and efficient when there is source separation in place because source separation usually leads to the best quality of the separated materials. However, sometimes source separation does not work properly (e.g. because of the low education level of people) or it is difficult to apply (e.g. because of a fixed and dense city infrastructure). Also, in the cases where source separation works well, there still exist significant amounts of recyclables in the mixed residual waste, and for reaching the challenging recycling targets, additional mechanical treatment and separation is needed. Mechanical treatment and separation are then used to improve material recovery and efficiency of energy recovery.

It is important to understand that both source separation and mechanical separation of materials are incomplete and after the separation, the residual part of waste still contains some recoverable materials and the separated recoverables contain impurities. This fact needs to be taken considered also in the evaluation of the environmental sustainability of waste treatment and separation. According to results from numerous life cycle assessment studies, it seems that the most important factors for the environmental sustainability of waste separation for recovery purposes are usually:

- The yield of recoverables (material recovery or recycling rate of the whole waste potential and avoidance of disposal of these materials)
- The replaced materials or fuels with the recovered materials (quality of the separated materials and demand for such materials and environmental impact of replaced virgin materials determine if there is a potential for reducing environmental impacts).

The strict material recycling targets in the EU necessity that also mechanical separation is included as a tool for increasing the recycling rate. More guidelines and rules are being developed on how the different mass flows for example from an MBT plant are calculated into the recycling targets. This leads to a clearer overview of the current mechanical recycling rate nationally, as well as EU-wide. At the end of the day, the development of various treatment and separation technologies is going on and better performance is achieved.

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