Influence of material alterations and machine impairment on throughput related sensor-based sorting performance

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Abstract

Experiments with sensor-based sorting (SBS) machinery provide insight into the effect of throughput rate and input composition on the sorting performance. For this purpose, material mixtures with certain compositions and particle size distributions were created from waste fractions and sorted at various throughput rates. To evaluate the sorting performance of the SBS unit (using near infrared technology) in dependence of the applied load, four assessment factors concerning the output fractions were studied: yield, product purity, recovery/product quantity and incorrectly discharged share of reject particles. The influences on the assessment parameters of light twodimensional (2D) particles in the input of a sorting stage and failing air valves in an SBS unit were evaluated for various input compositions at different throughput rates. It was found that a share of approximately 5 wt% 2D particles in the input had a similar negative effect on the yield as the malfunction of 20% of all air valves in an SBS machine at high throughput rates. Additionally, the failure of the air valves reduced the product purity of the sorting stage at increased throughput rates. Furthermore, qualitative observations concerning systematic effects of prior studies could be confirmed. Resulting graphs for a specific input composition of an SBS unit at varying throughput rates could be used to adjust the throughput rate to meet the exact demands for a sorting stage.

Keywords

Sensor-based sorting, sorting performance, purity, yield, recovery, throughput rate, input composition, NIR

Introduction

The amended EU Waste Framework Directive sets new requirements for waste management to improve sustainability and resource efficiency. To target the implementation of an enhanced circular economy specific recycling rates for municipal waste were announced. By 2030 the recycling of municipal waste must be increased to a minimum of 60 wt% (Directive (EU) 2018/851, The European Parliament and the Council of the European Union (2018b)). Additionally, the required recycling rate for plastic packaging waste (PPW) by 2030 will be 55 wt% (Directive (EU) 2018/852, The European Parliament and the Council of the European Union (2018a)). In 2016 an average of just 42 wt% of 16.3 million tonnes of European PPW was recycled. Germany reached 48 wt% and Austria 34 wt% (Eurostat, 2019). Besides these conditions, the DKR (Deutsche Gesellschaft für Kreislaufwirtschaft und Rohstoffe mbH) sets further quantitative and qualitative specifications in some countries, such as Germany and Austria. Amongst others this concerns minimum amounts of recyclables, as well as the nature and limit for impurities (Feil et al., 2017).

To attain these required recycling goals significant improvements, not merely concerning the collection but rather the treatment of waste, are necessary. The modern recycling of post-consumer PPW is carried out in automatic sorting facilities. The use of sensor-based sorting (SBS) machines for this material is state of the art and enables the separation of various types of plastic. Normally a cascade of near-infrared (NIR) units follows pretreatment steps such as bag opening and metal and film removal to guarantee the demanded quality of products (Jansen et al., 2015). The separation of different types of plastics is crucial for a successful circular economy. If certain impurities remain in the sorting product special treatment (e.g. the forming of polymer blends using compatibilizers) is necessary for the regeneration of plastic. Otherwise the recycling products will be of lower quality (‘downcycling’) (Ragaert et al., 2017). As a consequence, not only the quantity but also the quality assurance of PPW recycling products is important.

According to technical literature and manufacturer specifications for SBS machinery the performance of such technologies is

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subject to the load put on a respective unit. This load can be defined by the throughput rate (either volumetric or mass specific), material properties (e.g. particle size distribution) and the composition of the input material for a sorting unit (e.g. share of material that is supposed to be ejected via air shocks) (Cord-Landwehr, 2010; Redwave, 2019; Steinert, 2019).

To increase the performance of a sorting plant, not only the used technology in an SBS unit is relevant. The operation mode of the machine (e.g. the classification algorithm) as well as the functioning of prior processing and sorting units can have a severe influence on the sorting performance (Feil et al., 2016).

Generally speaking, there are two main external factors which determine the performance of an SBS machine: the throughput rate and the input composition (Feil et al., 2019). These factors are influenced by various aspects of a sorting plant. Besides others, the following are crucial:

1. Fluctuations of input quantity and quality (Feil et al., 2019; Martens and Goldmann, 2016)
    - Waste heterogeneity and seasonal or regional fluctuations
    - Batch-feeding of the continuously working sorting plant evokes mass flow peaks, for example through use of mobile loading technology (wheel loaders)
    - Inconsistent material discharge of processing machinery can result in under- or overfilling of aggregates (fluctuations throughout the week or day)
2. Screening efficiency (e.g. drum screen) (Feil et al., 2019)
    - Varying particle size distribution of heterogeneous waste
    - Low bulk density of plastics
    - Screen mesh size
    - Inclination and rotational speed (calibrated to achieve the residence time for a certain material flow rate)
    - Degree of filling (under- or overfilling)
3. Operation mode of other aggregates (Feil et al., 2016, 2017; Jansen et al., 2015)
    - Air classifier: air velocity defines which materials (films, beverage cartons, etc.) are separated
    - Feeding hopper: mechanical stress performed on the material might change the bulk density and therefore the throughput.

The aforementioned factors determine the mass flow (short and long term) and composition of the input into downstream SBS stages. In addition to the sensor performance, which can depend on the surface conditions of particles (e.g. moisture and roughness influence the classification) (Küppers et al., 2019), there are other influences which determine the efficiency of SBS:

- Number of sorting stages: rougher, scavenger and cleaner units. One step can either focus on yield or product quality (Feil et al., 2019).
- Singling of particles versus monolayer for spatial delimitation: basis for particle identification and selective separation (Feil et al., 2019).

A precise knowledge of possibilities and limits of the different units in a recycling plant is fundamental for operating ecologically and economically (Feil et al., 2017). The current research at the Chair of Waste Processing Technology and Waste Management of the Montanuniversität Leoben aims to quantify the impact of input composition and throughput rate (occupation density) on SBS. Küppers et al. (2020) found the following systematic effects from prior SBS trials:

- With increasing throughput rate the yield, recovery and product purity decrease while the product quantity increases.
- With increasing eject share in the input the yield, recovery and product purity increase as well as the product quantity.

This study focuses on input specific effects of varying particle sizes and two-dimensional (2D) disturbing material (e.g. from poorly functioning air classification) in the input and the influence of failing air valves on the sorting performance of an SBS machine.

Materials and methods

In the conducted series of tests, the separation of post-consumer polyethylene terephthalate (PET) from polyolefin (PO) was studied. In all experiments PET was intended to be discharged via air shocks while PO was intended to be rejected (no ejection through air shock).

Materials

The examined material originates from a shredded (<30 mm) air classifier heavy fraction of separately collected PPW material. Films, metal particles and other impurities were removed to generate a defined initial state, ensuring correct classification of all particles in the test material. This way the uncertainty factor ‘sensor’ was excluded from the study, which meant that all observed variations were due to sorting and not to sensing errors. Both the PET and the PO fractions were sorted and analysed multiple times with the SBS test stand in advance to ensure that both materials had 100% purity before the start of the experiments.

To generate a 2D fraction with assured correct recognition as reject material, standard paper (80 g m^{-2}) was cut into pieces of approximately identical size. The side length of the squares was about 5.2 cm (in the range of 4.5–5.5 cm).

Equipment

The experimental SBS setup, engineered by Binder+Co AG, is used to separate material according to different sorting criteria via a compressed air nozzle bar. As shown in Figure 1 a colour line scan sensor (VIS), an induction sensor and the employed NIR line scan sensor (EVK Helios-G2-NIR1) are part of the test stand but only the NIR line scan sensor was used for the experiments. An upstream vibrating conveyor with an optional feeding hopper was

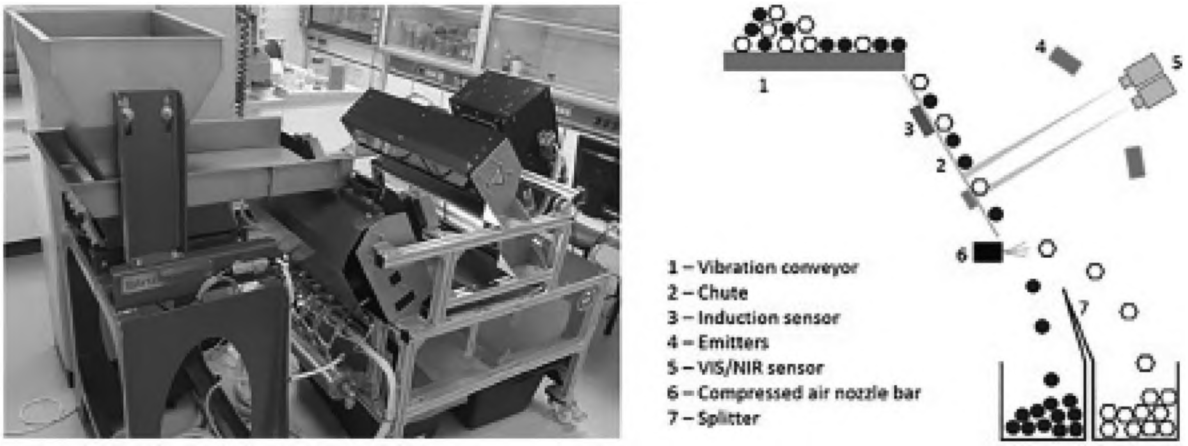

Figure 1. Experimental setup for sensor-based sorting trials.

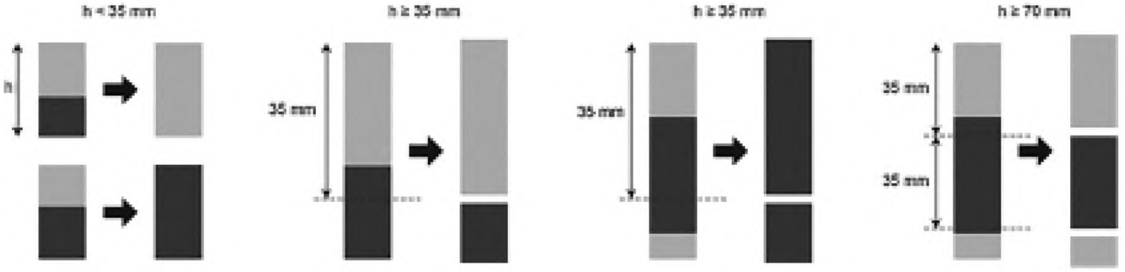

Figure 2. Classification mechanism depending on particle height (h).

used to feed the sample material to the chute sorter. The working width and length are 500 mm and 455 mm, respectively.

An infrared lamp is utilized as the emitter for the setup. The emitted radiation interacts with the near-surface molecules of the particles and is reflected, absorbed and/or transmitted depending on the chemical composition of these particles. The dispersed reflected radiation strikes the NIR sensor and is detected. Subsequently, this radiation (wavelength range: 1000–1700 nm) is converted into an electrical signal. A spatial pixel is 1.60 mm wide due to the geometry of the experimental setup. Depending on the sliding speed of the particle on the chute, the length of the pixel may vary but is always smaller than 1.60 mm. The frame rate of the line scan sensor is always 476 Hz with an exposure time of 1800 µs.

The sorting algorithm of the test stand digitally segments objects >35 mm in conveying direction. Every object is then classified individually as the material whose false colour pixels dominate the object. This is especially relevant for overlapping particles of different material. Figure 2 shows different scenarios depending on the particle height and the composition of a detected and segmented object.

A built-in data acquisition software from Binder+Co AG recorded the material specific number of detected objects after digital processing and classification.

Methods

In the course of the investigations, 204 experiments were carried out in total. These were organized in three phases, which in turn consisted of several test series for each generated input composition (Table 1):

Phase 1: reference trials
Phase 2: simulation of a failing block of air valves (on 20% of the working width)
Phase 3: simulation of poorly functioning upstream air classification (added paper)

The results from phase 1 constituted the baseline for the maximum machine efficiency depending on the respective throughput rate and input composition. The scenario of a failing block of air valves (phase 2) represented a tangible reference value to assess the effect of other factors on the sorting performance. In phase 3 the influence of 2D material, classified as reject (PO), was investigated. The number of experiments for the three phases and respective test series can be seen in Table 1. Trials for each test series (different mixing ratios) were conducted at varying throughput rates in the range of 5–350 kg h^{-1}. The exact rerun of a certain throughput rate was not possible, as the focus was to ensure a steady material feed. Accordingly, all trials in each test series were conducted with different throughput rates. Specific mixing ratios of PO and PET, e.g. 95/5 = 95 wt% PO and 5 wt% PET, were created as input materials. The mixing ratio 95/5 represented the base mix. Further PET particles were added to create the other mixing ratios. Depending on the mixing ratio, approximately 18,500–34,500 PET and PO particles were used for each experiment, according to the data acquisition software. For the

Table 1. Number of experiments for the different trial phases.

Mixing ratio (PO/PET)	Phase 1: reference trials	Phase 2: failing block of air valves	Phase 3: failing air classifier
95/5	10	21	6
90/10	11	23	-
80/20	11	20	6
70/30	10	19	6
60/40	12	17	6
50/50	10	17	5
Total	64	117	23

PET: polyethylene terephthalate; PO: polyolefin.

Table 2. Assessment factors for trial assessment (Feil et al., 2016).

Assessment factor	Abbreviation	Equation	
Recovery	R	$R=\frac{\dot{m}_{Eject}\left[\frac{t}{h}\right]}{\dot{m}_{Input}\left[\frac{t}{h}\right]}*100\,\%$	(1)
Yield	R_w	$R_W=\frac{\dot{m}_{Eject}\left[\frac{t}{h}\right]*c_{PET\ in\ Eject}[\%]}{\dot{m}_{Input}\left[\frac{t}{h}\right]*c_{PET\ in\ Input}[\%]}*100\,\%$	(2)
Purity	P_m	$P_m=\frac{\dot{m}_{PET\ in\ Eject}\left[\frac{t}{h}\right]}{\dot{m}_{PO\ in\ Eject}\left[\frac{t}{h}\right]+\dot{m}_{PET\ in\ Eject}\left[\frac{t}{h}\right]}*100\,\%$	(3)
Incorrect PO discharges	PO_{Eject}	$PO_{Eject}=\frac{\dot{m}_{Eject}\left[\frac{t}{h}\right]*c_{PO\ in\ Eject}[\%]}{\dot{m}_{Input}\left[\frac{t}{h}\right]*c_{PO\ in\ Input}[\%]}*100\,\%$	(4)

PO: polyolefin.

trials in phase 3 paper was added to the mixture. To each mixing ratio 5 wt% of the existing total mass were added on top.

Experimental procedure

For each test series a different mixing ratio of PET and PO was generated to investigate the influence of varying reject and eject shares in the input and interdependencies with other factors. The mass of each input mixture was recorded. Prior to every trial the mixture was thoroughly mixed ensuring even distribution of the different materials in the feed. The mixture was fed with the vibrating conveyor. For each trial, the test time was recorded resulting in the throughput rate of each experiment based on the ratio of input mass to test duration. The PET particles were classified as ‘eject’ material and discharged via compressed air. False classification mainly occurred due to the overlapping of reject and eject particles, potentially evoking the discharge into the wrong output. The composition of the respective eject fraction was subsequently analysed using the same SBS machine. For trials with paper in the input material all paper particles were removed prior to analysis, enabling assessment of its effect on incorrect discharge of PO and yield of PET only.

Statistical evaluation

For the online analysis of both the input material of each experiment and the eject fraction a data acquisition software was used. The number of detected objects for each material (PET, PO, paper and ‘unknown’) was recorded. The number of detected objects in the input material allows conclusions concerning the sorting performance. The number of detected objects during the analysis of the eject fraction provides information on recovery, yield, purity and incorrectly discharged PO particles. The analyses of the eject fractions were conducted at low throughput rates to ensure particle separation, thus reliable data.

The results were evaluated with respect to recovery (R), yield (Rw), purity (Pm) and incorrect PO discharges (PO_{Eject}). For the calculation of each assessment factor the equations in Table 2

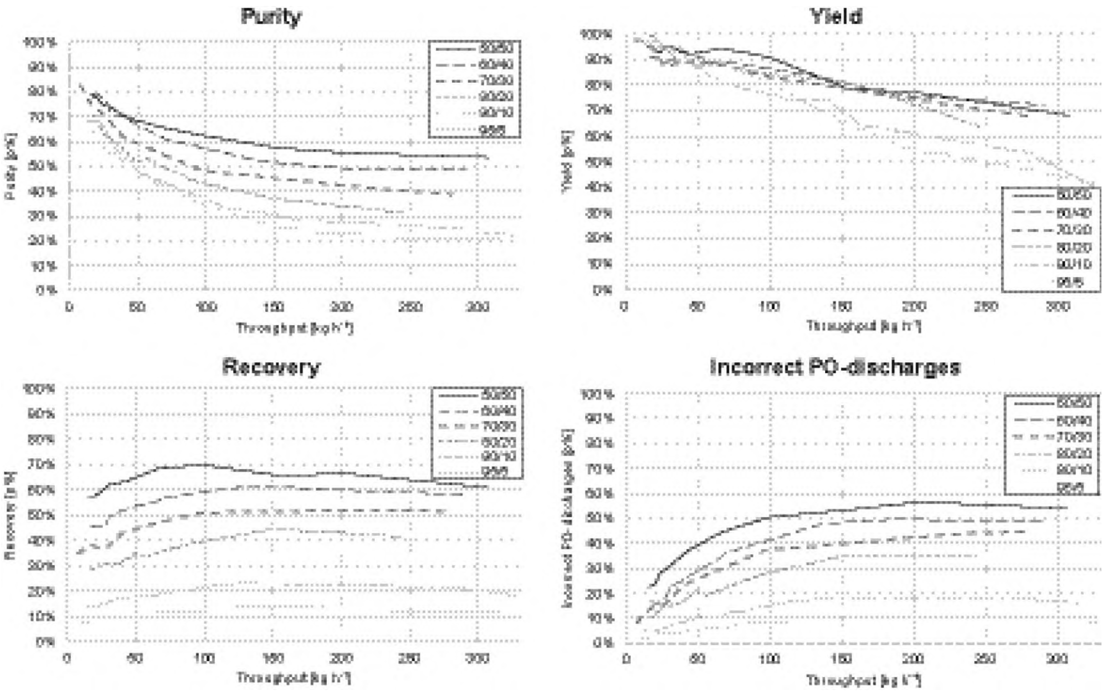

Figure 3. Effects of input composition (PO/PET) and throughput rate on yield, incorrect PO discharges, purity and recovery.
p%: particle percentage; PET: polyethylene terephthalate; PO: polyolefin.

were used. The variable $\dot{m}$ describes the mass flow (input, output, recyclable material or impurities) in tonnes per hour while the concentration c in input or output is given as mass percentage.

All results presented in this study were evaluated on the basis of particle related recovery, yield, purity and incorrect PO discharges as this is most suitable for the assessment of an SBS unit. Hence, in the aforementioned calculations the mass flow complies with the number of objects in a defined time range. As a result, the assessment factors are given in particle percentage (p%) instead of mass percentage. The particle-related information can be converted into mass specific data by using material specific correction factors, taking into account the particle specific average grammages of eject and reject fractions.

Results and discussion

All experimental results are assessed on the basis of yield, purity, recovery and the share of incorrectly discharged PO particles. The first experimental results are those of the reference trials, quantifying the effects of different eject and reject shares in the input composition as well as the influence of the throughput rate on sorting efficiency. Subsequently the impact of the 2D material on the performance of an SBS stage is quantified and compared with the effect a defective block of air valves has on the sorting efficiency.

Reference trials

At throughput rates under 15 kg h^{-1}, yields >97 p% were achieved independent of the input composition. The yield was found to decrease in a linear fashion for increasing throughput rates. This decrease is caused by the overlapping or contact of PET and PO particles resulting in wrong classification of PET particles due to unfavourable digital segmentation.

For input compositions 95/5 and 90/10 the gradient is steeper than for more balanced input mixtures reaching about 50 p% yield at approximately 270 kg h^{-1}. The different gradients can be due to the fact that the experiments with PET shares >10 wt% had to be conducted by using the hopper to handle the input material, thus causing better deagglomeration, while trials with PET shares of 5 wt% and 10 wt% were conducted with the vibrating conveyor only. Additional experiments support this theory, showing that the input composition had no impact on the yield.

However, trials with coarser, rectangular particles created an exponential decrease in yield (Küppers et al., 2020). The form of the respective yield function might be dependent on the particle size distribution of the input material (Figure 3) in dependence of the sorting algorithm. This bears potential for further research, for example experiments regarding the effects of object versus pixel cluster classification on sorting performance in various particle size ranges.

The incorrect PO discharge (Figure 3) increases in the form of a saturation curve for all input compositions. As correct classification of PET and PO pixels was ensured, only two reasons for incorrect PO discharge persist:

- Overlapping or contact of PET and PO particles resulting in wrong classification of PO particles due to unfavourable digital segmentation
- Entraining of nearby PO particles via air shocks that are supposed to only eject PET particles

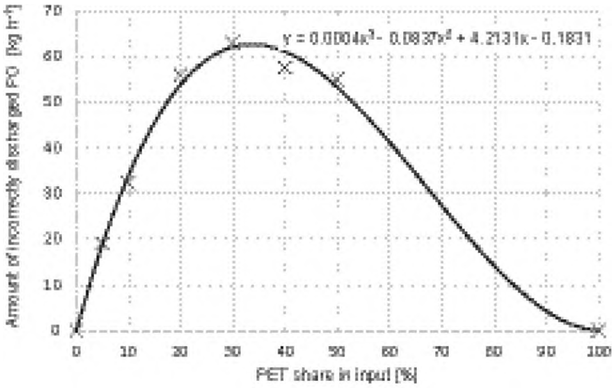

Figure 4. Quantity of entrained PO into the eject fraction per hour at throughput rate 200 kg h^{-1} and respective approximation function.
PET: polyethylene terephthalate; PO: polyolefin.

The latter reason is directly linked to the pressure that is used for the separation of eject particles with the air valves.

The forms of purity and recovery functions arise from the form of the saturation curve of the incorrectly discharged PO particles and from the linear decrease of the yield. The latter functions dictate the course of purity and recovery functions in dependence of the throughput rate.

The limit for each saturation curve of incorrectly discharged PO particles is always a multiple of the PET share in the respective input composition. This factor ranges from 2 for mixture 95/5 to 1.1 for mixture 50/50. The decreasing slope of the curve of incorrect PO discharges can be attributed to the differing numbers of PO particles that are entrained at specific throughput rates, reducing the probability that more PO particles are incorrectly discharged if the throughput rate is increased furthermore.

The share of entrained reject particles is of importance because firstly it determines the eject purity and secondly the entrained reject particles might consist of lost recyclable material that otherwise could be separated in downstream sorting stages. To know how much of this material is lost per time unit, the share of PO particles entrained into the eject fraction must be related to the total quantity (kilograms per hour) of input material for a respective sorting stage and not to the relative share of PO particles in the input material. Figure 4 shows the amount of PO particles (with regard to the total input) that is entrained into the eject fraction at a specific throughput rate, in this example 200 kg h^{-1}, for different input compositions under the assumption that PO and PET particles have the same weight. The maximum value of this function varies in dependence of the ratio of reject and eject material in the input composition.

Two variables affect the quantity of entrained PO:

The share of eject particles causing a respective number of air shocks per time unit that could potentially entrain reject particles – the higher the share of eject particles the more air shocks are triggered.

- The share of reject particles in an input mixture that could be incorrectly discharged – the higher the share of reject particles the more reject particles could be entrained.

In industrial applications usually the material fraction that dominates a mixture is rejected, while the minor fraction is ejected. Accordingly, no trials were conducted with eject shares $>$50 p% (Figure 4). If no PO was present in the input (100% PET content) the amount of entrained PO would be 0 kg h^{-1}. On the contrary, at 0% PET content no air shocks would be triggered resulting in 0 kg h^{-1} of incorrect PO ejection, if no false classification of PO as PET is presumed.

The right-skewed distribution function indicates that the maximum amount of losses occurs for an input mixture that comprises one-third eject and two-thirds reject material (particle and not mass related). Accordingly, neither the share of incorrectly discharged PO particles nor the eject purity are directly correlated to the entrained reject share. As a result of this observation the highest loss of reject material into the eject fraction is to be expected for mixtures with one-third eject material particle percentage and two-thirds reject material particle percentage. This maximum can be explained by the fact that one eject particle bears the chance of entraining multiple reject particles into the eject fraction and not vice versa.

Influence of increased 2D material share (paper) and a failing block of air valves

Figure 5 shows that a failing block of air valves decreases the eject yield in accordance to the working width it covers (in this case 20 p% ±5 p% as the block of valves also covers 20% of the working width) independent of the input composition or throughput rate.

The decrease of entrained PO is throughput dependent and reaches approximately 4–10 p%. The respective maximum decrease is reached at moderate throughput rates of 60 kg h^{-1} (PET-rich input mixtures) and 150 kg h^{-1} (PO-rich input mixtures).

As incorrect PO discharge is reduced to a lesser degree than PET yield the purity of the eject fraction showed a slight overall decrease of $<$5% due to the failure of the air valves. This can be attributed to the fact that PO particles, sliding over the area that is covered by the inactive block of air valves, can still be entrained by air shocks from working air valves nearby. Accordingly, it is presumed that the failure of multiple blocks of air valves has a bigger effect on the product purity if the blocks are not directly adjacent to one another.

The results show that the presence of 2D material in the feed of an SBS stage at low throughput rates has little to no effect on the yield but leads to a decrease of approximately 20 p% in yield for high throughput rates. A similar trend is apparent for incorrectly discharged reject material whose share decreases by approximately 10%. Accordingly, the presence of 2D material (5 wt% added) and inactive air valves (covering 20% of the working width) had a similar repercussion on the sorting process.

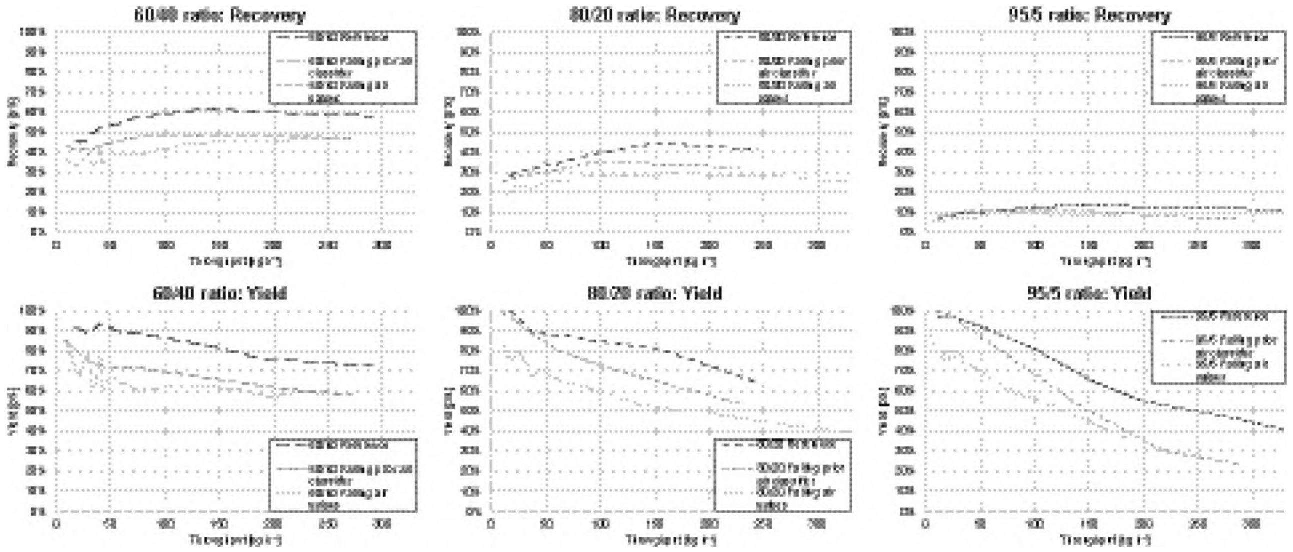

Figure 5. Influence of failing air valve blocks and 2D material on sensor-based sorting as functions of the throughput rate for various input compositions (PO/PET: 60/40, 80/20 and 95/5).
PET: polyethylene terephthalate; PO: polyolefin.

Conclusion

Quantitative investigations allow for particle specific assertions concerning the sorting performance of an SBS stage with regard to recovery, yield, purity of the eject fraction and share of incorrectly discharged reject particles. To transfer such information to mass specific statements the average grammage of eject and reject particles must be known. The given results show systematic effects of various factors that were investigated: input composition, throughput rate, presence of 2D material in the input material and malfunction of air valves on the machine performance. Further factors, either material or machine specific, are of vital relevance for the sorting performance; these are principle of the sorting algorithm (e.g. segmentation of particles), particulate weight, feeding method (e.g. type of vibration conveyor) and particle shape. Additionally, the influence of the particle surface condition (e.g. organic defilements, labels and adherent particles) on the classification must be taken into consideration to determine the overall sorting performance.

The following assertions can be made based on the conducted trials:

- Yield is not affected by the share of eject and reject particles in the input. Yield decreases with rising throughput rate.
- Incorrect discharge of PO particles increases in the form of a saturation curve with rising throughput rate. The limit for the maximum incorrect discharge is a multiple (factor 1.1–2) of the PET share, thus dependent on the input composition. The absolute quantity of entrained reject particles is highest for approximately one-third eject share although the relative loss of PO particles is highest for 50 wt% PO share in the input.
- Purity of the eject fraction decreases with increasing throughput rate. Purity of the eject fraction decreases with decreasing eject share in the input composition, whereby the influence of the eject share is enlarged with increasing throughput rate. Purity and recovery are functions of yield and incorrectly discharged reject particles.
- 2D material (classified as reject) in the input of a sorting stage proved to reduce the yield and incorrect reject discharge at increased throughput rates. For low throughput rates the influence of 2D material on sorting performance was negligible. A 5 wt% of 2D material had a similar effect on the sorting performance at high throughput rates as the failure of a block of air valves covering 20% of the working width of the SBS setup, whereas the effect of the failing air valves affected the sorting efficiency also at moderate throughput rates: incorrect PO discharge was reduced by 4–10 p%, peaking at high throughput rates for all input compositions. The yield was reduced by 20 p%, independent of the input composition.

To attain more comprehensive knowledge on interdependencies and the relevance of various machine and material specific influence factors, further trials with regard to the effects of e.g. machine design (chute versus belt sorter), air nozzle design, applied air pressure and particle properties should be conducted. Such information can enable the modelling and optimized configuration of throughput rate and machine settings to attain optimal machine and plant performances.

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