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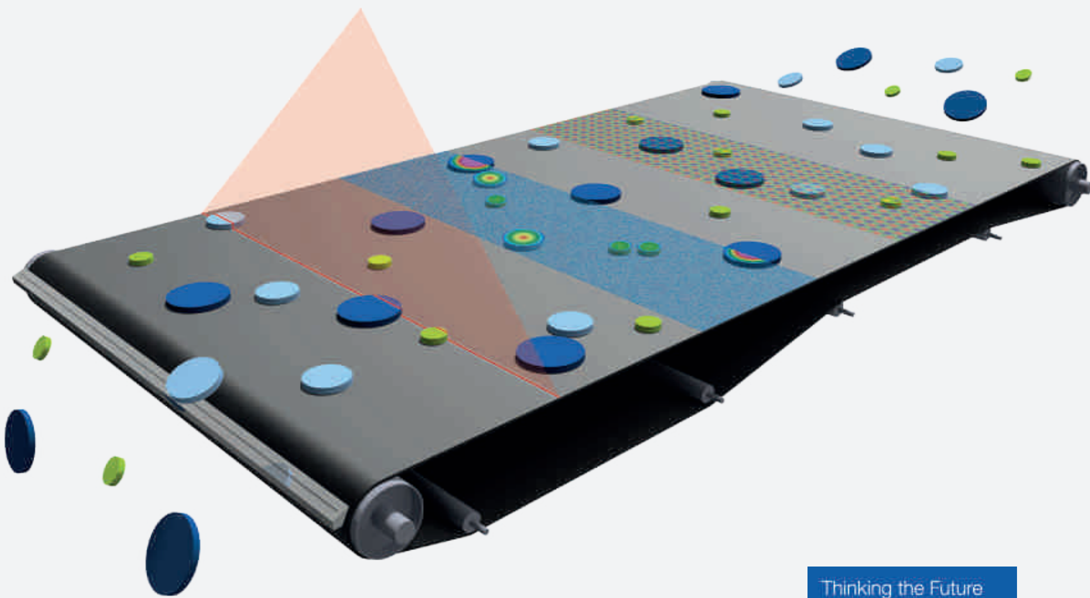

Thinking the Future
Zukunft denken

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Relevance and challenges of plant control in the pre-processing stage for enhanced sorting performance

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Abstract

To increase recycling rates many technological improvements can be made within sorting (processing and sorting on article basis) and recycling (processing and sorting on particle basis) of waste. This paper discusses such technological improvements, focussing on the potential of pre-processing (pre-shredding, screening, air and ballistic separation) in sorting plants. For this purpose, the general structure of state-of-the-art sorting plants is briefly introduced.

Material flow characteristics such as input material composition or volume flow, have high impact on the performance of such sorting plants and are discussed accordingly. By adjusting parameters such as shredder speeds or screen cuts, these characteristics can be set to adjust the plant in accordance with variations in the input material. Such adaptions can only be made if the material flow data is reliable and available in nearly real-time (e.g., through built-in sensors). The related challenges in data acquisition, data analysis, and plant control are discussed.

Finally, a case study is presented to demonstrate the potential of adaptive plant control: Through data derived from near-infrared sensors the load of two processing

lines could be adjusted, resulting in significantly increased plant performance: Yield of product fractions from 3D-/heavy processing lines could be increased by 3-15 wt%.

1 Introduction

Member states of the European Union have implemented different collection and recycling systems for various types of packaging wastes to achieve environmental benefits through (a) minimizing/avoiding littering and landfilling of packaging wastes and (b) substituting primary raw materials with the obtained recyclates from recycling. Compared to other end-of-life options such as incineration, mechanical recycling of packaging waste is advantageous because of the achieved energy savings and reduced greenhouse gas emissions. (European Union, 2018; Ragaert et al., 2017; Perugini et al., 2005; Astrup et al., 2009)

Since (mechanical) recycling of packaging wastes is environmentally advantageous, a higher material recirculation is encouraged on a political level (Circular Economy Action Plan; Packaging and Packaging Waste Directive). For example, the new EU Packaging Directive is being discussed, which is demanded to include requirements for minimum recycling contents of 30 wt% for plastic packaging by Plastics Europe. (Grüner Punkt; 2021)

State-of-the-art material recirculation of packaging materials is achieved in three steps: (i) collection of packaging wastes, (ii) pre-sorting (production of preconcentrates on an article basis), and (iii) recycling (washing, sorting, and processing into a product – mostly on particle/flake basis), see Fig. 1. Type, extend and performance of each step, from waste collection over pre-sorting up to recycling, is highly relevant for maximising the recycling of valuable materials, i.e., keeping more packaging in closed material cycles.

Fig. 1: Relevance of collection-, pre-sorting and recycling-performance (80% exemplary performance) for the overall achieved recycling performance

As can be seen in Fig. 1, each step, from collection to recycling, contributes to the overall recycling quota, resulting in approximately 50% recycling rate for any article, if the performance of each step is 80%. According to the Pareto principle, each of the three steps should be improved equally, to achieve maximum improvement of overall recycling rate. Such overall improvements in the value chain inhibit the increased losses in certain steps, that cannot be regained through improvements in downstream steps (e.g., in the recycling process).

In case of the collection of waste this can be particularly achieved by political/ organisational measures, e.g., by introducing a deposit system for a certain packaging, through the provision of dustbins in public places to prevent littering or encouraging optimized waste separation through public campaigns.

Pre-sorting and recycling performance are mostly driven by technological improvements. However, certain aspects such as quality control of product fractions are to this day often handled manually. (Kranert et al., 2017)

In the past, most technological advances in pre-sorting have been made through improvements and expansions in sensor-based sorting (SBS) cascades, as increased processing power of computers allowed for more sophisticated sorting algorithms, resulting in improved performances of optical sorting machinery—primarily near-infrared (NIR)-based sorters for the sorting of (plastic) packaging wastes.

However, all sorting machinery, in particular optical sorters, require an even material feed, ideally with a limited particle size ratio (ratio of maximum to minimum particle size). Therefore, comprehensive pre-processing of collected waste is of utmost importance to achieve high pre-sorting performance in waste sorting plants. (Feil et al., 2018; Feil et al., 2019 Feil et al., 2021)

In the present paper, the overall design of such a sorting plant is explained to discuss various parameters that can be adjusted in pre-processing, allowing for increased sorting performance of downstream processing lines that are mostly comprised of (optical) sorting machinery. Subsequently, the potential and challenges of using sensors for adjustments in the pre-processing of waste is discussed, ending with an example of sensor-based adaptive plant control in pre-processing, resulting in improved sorting performance of downstream sorting technology.

2 Structure of sorting plants

In most sorting plants, the input waste is delivered to an input storage. This can comprise of, e.g., simple boxes made of concrete blocks or underground bunkers. From here the input material is fed to the sorting plant by means of wheel loaders, cranes, or with similar machinery. The sorting system itself can be divided in two sections: (i) pre-processing stage and (ii) sorting stage (Feil et al., 2021).

In pre-processing, the waste stream is treated to allow for optimal sorting of valuables, residues, and impurities in downstream sorting lines. For this purpose, mostly pre-shredders (this also includes bag/bale openers), sieves, air classifiers, and ballistic separators are utilised.

- **Pre-shredding** allows for opening of bales, breaking up agglomerates and clamped materials, limitation of maximum particle size, and selective shredding for material enrichment in different particle size fractions. Additionally, pre-shredders dose the material to the sorting plant, creating a material stream, potentially displaying fluctuations. In sorting plants of lightweight packaging wastes (LWP), most often bag openers are installed.
- Most often the pre-shredder is followed by one or multiple **sieving stages**. In LWP sorting plants, most often drum screens are utilised for screen cuts of approx. ≥ 40 mm. Depending on the size of such plants, about four screen cuts must be implemented through drum screens in the screening stage. Finer screen cuts (about 20 mm) are usually implemented as vibratory sieves. Despite the separation of oversize and fine impurities the screen cuts are chosen to enrich certain materials in specific particle size ranges (to capitalise on the selective shredding, up-stream) and to create material flows with sizes that fit to the processing lines that follow the screening stage. Additionally, the performance of down-stream machinery is optimal when limited particle size ratios (1:3 to 1:4) are present in all processing lines (Feil et al., 2021).
- Often **air classifiers** are positioned as the first processing units in the processing lines after the screening stage, while **ballistic separators** are implemented afterwards (Kleinhans et al., 2020). In such cases, the air classifiers are used to produce relatively clean film/2D/light fractions, while the ballistic separators must ensure high purities in the 3D/heavy fractions,

potentially also serving as an additional screening stage, depending on the chosen paddle mesh. Nonetheless, both machine types can also be used separately from each other, always with the goal of separating 2D/light and 3D/heavy fractions (Möllnitz et al., 2020). This enriches valuable materials in both fractions and reduces the volume of 3D material flows additionally, allowing for increased throughput rate and performance in the 3D processing lines as the 2D material is reduced. Valuable fractions in the 3D lines are ferrous and non-ferrous metals as well as various plastic fractions and beverage carton.

In each processing line of the sorting stage, several sorting machines are implemented, usually after air classification. Those units are characterised by the fact that they separate specific material types, in contrast to pre-processing units mentioned above, which prepare (at most enrich) certain material. Sorting machines and their primary products are:

- Magnets – Production of ferrous product;
- Eddy current separators – Production of non-ferrous metal product;
- Optical sorters (predominantly NIR- but also induction- and colour- based sensors) – Production of pre-products such as PP, PE, PET, PS, beverage carton, Paper, RDF. (Kleinhans et al., 2020)

Such sorting machines (mostly optical sorters) can also be used as cleaners, further enriching the respective product fractions created beforehand to reach increased product qualities. Other optical sorters are used as scavengers, obtaining valuables from residue streams that were lost by upstream sorting units. Sorting machinery, that is used to create a product fraction out of a mixed material stream are defined as roughers. (Feil et al., 2021)

Many product streams undergo manual quality control during which valuable materials are recirculated to the process, while residues can be specifically passed to the residues fraction.

2.1 Relevance of material flow characteristics for plant performance

To adjust a sorting plant a multitude of parameters can be set, depending on the combination/design of processing stages/machinery used within a process. The available parameters can be set to affect the following main material flow characteristics:

- The **material composition** highly affects the performance of any processing unit, as the behaviour of any particle type differentiates in any pre-processing unit. For example, films are much more prone to remaining at its particle size during pre-shredding and tends more to be pulled through a screen mesh. Additionally, the likelihood to be entrained into any product of a sorting machine is substantially higher than for heavy three-dimensional particles. Accordingly, the adjustment of any material composition bears high potential for alterations in machine performance. (Küppers, Schlögl, et al., 2020; Küppers, Seidler, et al., 2020)
- The **particle size range** affects the performance of any processing and sorting machine. While, e.g., high amounts of very fine material in an otherwise rather coarse material stream, compared to the screen cut, improve the performance of screens (such particles are much more prone to pass the mesh immediately), especially for sensor-based sorting these fines often result in reduced yield and/or purity, thus reduced sorting performance. If such fines are magnetic, these particles can hardly be removed by an over belt magnet, while they tend to remain in an eddy current field, where they cannot only hinder the discharge of non-ferrous metals but also constitute a risk to the durability of this machine type.
- The **volume flow** constitutes one of the most important factors for the dimensioning of shredders, sieves, air classifiers, magnet separators, and eddy current separators. Accordingly, the adjustment of this characteristic in any plant and processing line allows for manipulation of machine and plant specific performance adaption (Curtis et al., 2020). The volume flow can be tied to other characteristics, as the input composition: If, e.g., the bulk density of the input is reduced, due to a change in material composition (e.g., higher share of film), this causes an increased input volume flow, which in turn reduces, the performance of built-in sieves, as those machines are designed for specific volume flows. Such a sieving performance reduction can result

in shifts of the volume flow in all downstream processing lines, evoking the performance of all processing machines to change.

- The **area flow** is defined as the flow of projected object area as seen by a sensor, mounted over a conveyor belt. This characteristic is mostly important for optical sorters as classification and thus separation performance is highly dependent of the size of the specific area flow (Curtis et al., 2020). Ideally, the occupation density (area on a belt that is occupied by material) does not exceed 30 area-%. The higher the occupation density (and the closely linked area flow), the lower the performance (yield and product purity) of any optical sorter in most cases (Küppers, Schlögl, et al., 2020; Küppers, Seidler, et al., 2020; Kroell et al., 2022). This is due to the increased probability of false classification of objects and the resulting reduced sorting performance that persists at increased occupation densities.

2.2 High-impact parameters in sorting plants

In sorting plants, several parameters can be adjusted to improve the performance of such a plant. In general, the significance of these parameters is linked to the point in the processing line, where they can be set. The earlier this can happen, the higher the impact on the whole processing line is as all downstream machinery is affected by such parameters. Additionally, changes (positive or negative) in such parameters multiply with each machine, since the reduced or increased performance of each unit negatively or positively affects the performance of the following one. Hereafter, several of potential high-impact parameters are described.

- Composition of input material**.** As single plants are often fed with materials from several collection systems, the input composition can vary strongly, e.g., from day to day or from shift to shift. Each processing plant is designed for a specific input composition. Limited fluctuations can occur while the full functionality of the plant is still ensured. However, extreme fluctuations in the input composition can affect the performance of single machines, processing lines or of the whole plant. Accordingly, mixing two input materials of different compositions can allow for improved plant performance, while processing of such input materials separately might inhibit reaching a plants full potential.

- Rotational speed in pre-shredders. Pre-shredders have several parameters like size of the discharge grate, speed of crushing tools or interval size for changes in direction of crushing tools. If the crushing tools are located on several shafts the speed and interval changes might be controlled independently from each other to allow not only for the right amount of particle reduction but also generating reduced volume flow fluctuations (Feil et al., 2019).
- Screen cuts. In sieves, the selected screen cut is the most obvious parameter for plant control. Despite its obvious purposes (creating material streams with specified particle size ranges, and enrichment of certain material fractions) the most important function of a screen is the split of the in going volume flow into output streams that have the right size for downstream processing lines and built-in sorting machinery. By using a progressive mesh size and splitting the resulting sieve underflow in accordance with the dimensions of downstream processing lines a suitable volume flow split can be achieved. In a multitude of LWP sorting plants movable, bi-directional belts are positioned under drum screens, allowing for this adjustment of the screen cut.
- Air flow in air classifiers. The selected air flow significantly affects the selectivity of air classifiers. Depending on the air flow the material composition and the correlating bulk density in light and heavy fraction are manipulated significantly (Pretz et al., 2020). This way the load on processing lines for light and heavy material is adjusted, as both, volume and area flow, are affected likewise. Regarding the material composition in light and heavy processing lines, this results in changes regarding the share of film and 3D plastics in each line. Borderline objects, like food trays that are characterised by properties which can be associated with light *and* heavy fraction objects (e.g., trays for cheese packaging that contain a film-like lid). Those are shifted from one output fraction to another, when resetting the parameter “air flow” in an air classifier.
- Paddle angle in ballistic separators. The parameter “paddle angle” affects the selectivity of ballistic separators similarly to the air flow in air classifiers. However, the underlying mechanisms of a ballistic separator are different to those of an air classifier. Contrary to popular belief, ballistic separators not only split two-dimensional from three-dimensional objects. Additionally, to the shape of an object the ductility, flexibility, elasticity, and weight of an object affects the separation into the 2D or 3D fraction. On ballistic separators,

typical borderline objects are foams (from mattresses), beverage cartons, and cardboard boxes. The steeper the paddle angle, the more of the incoming material flow is yielded into the 3D fraction and vice versa.

The potential of the afore mentioned parameters is often not capitalised on by many plant operators. This is due to the high complexity modern sorting plants exhibit. Accordingly, most plants constitute a black box and only a limited number of parameters is controlled manually (e.g., rotational speed of the shredder for throughput adjustment). Automated plant adaptions could exploit such unused potentials if their control could be monitored in near-real time and assessed adequately.

3 Challenges in plant control

As described above, the adjustment of parameters bears high potential for continuous plant optimisation. However, several challenges must be overcome to enable an automated plant control. These challenges are related to

- the sensors used to obtain material flow and machinery data,
- the process control algorithm that is used to transform the data into an automated response (parameter adaptation), and
- the actuators, directly affecting the operating principle of a pre-processing or sorting machine. (Khodier et al., 2019)

The reliability of data derived from a sensor is dependent on (i) the type of measurand (e.g., volume, area, material composition), (ii) the machine that is controlled, (ii) the desired effect that is to be attained, and (iv) its overall validity. The type of measurand derived from a sensor (e.g., volume flow) is relevant as it may be used to adjust the respective volume flow dependent parameter (e.g., screen cut). However, this parameter might be set with the aim to change a different target value (e.g., area flow) that is more relevant for the performance of downstream optical sorters. Accordingly, the basic information that can be derived from sensor data must at least correlate with the target value (in this case the area flow). An example for such a correlation is given in Fig. 2., displaying volume and occupation density (or area flow) at the same position in a process line for light weight packaging sorting.

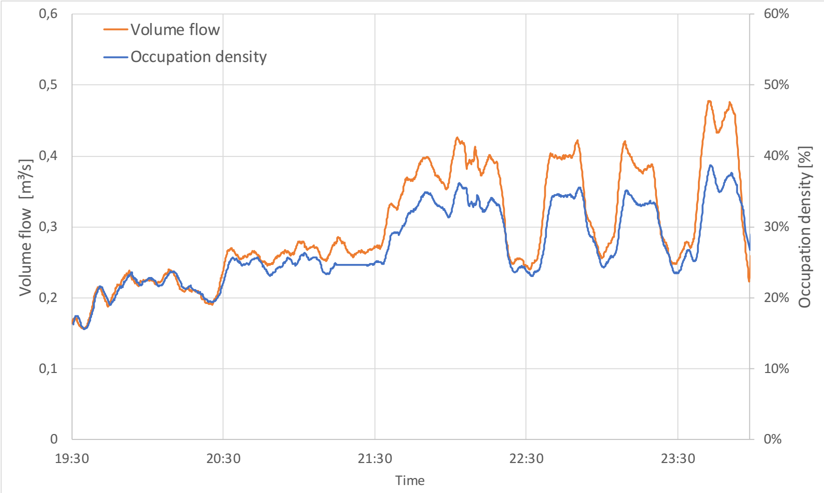

Fig. 2: Comparison between occupation density (strongly correlated with area flow) and volume flow on a belt conveyor

As depicted in Fig. 2., a high correlation between occupation density and volume flow can be observed. However, the extent of changes in one measurand is not directly transferable to the other one. For this case, one can expect that the correlation between both measurands is sufficient as long as the occupation density is low enough to keep object overlay to a minimum when comparing data before 21:30 with data after this point in time. Additionally, changes in the input composition might lead to a change in the proportion of occupation density to volume flow. How strong and how stable the correlation between measurand and target value must be, must be decided on a case-by-case basis. Ideally, the measurand type directly complies with the target value and correlation is strong. The overall validity of a measurand is dependent on the suitability for the application (a certain NIR-sensor may be ideally suited for assessing the share of paper in a material stream but not for differentiation of plastic types), on the quality/versatility of the sensor itself but also on the environmental conditions. For example, in a dusty environment a volume flow sensor that is less precise but generates more stable data is better suited for volume flow monitoring than a very precise sensor that is strongly affected by a dusty environment. Especially in the waste/recycling sector this can entail case specific selection of different sensors for similar or even identical tasks.

The algorithms used for process control include the raw data pre-processing (deriving usable data from detected signals – for NIR-sensors this might result in normalization, smoothing and deriving the raw data). The resulting compressed data, in form of, e.g., false colour pixels, volumetric information, can then be further processed, to compensate for systematic misidentifications, handling error values, or weighting the data stream (e.g., transforming a pixel-related sensor measurements into mass-based material flow characteristics [Kroell et al., 2021] or emphasizing certain material classes). Additionally, volumetric and areal information can be used to allow for object recognition which can strongly impair or improve the validity of data, depending on the circumstances (material presentation to the sensor, material characteristics, etc.) and algorithm. Obviously, the utilisation of sensor data from built-in optical sorters represents an attractive opportunity to capitalise on data that is otherwise used for sorting purposes only. Here the problem is, that the main focus of the algorithms in such sorting machines is correct classification and separation of eject and reject material. This does not mean, that the data generated throughout this process is reliable for the monitoring and assessment of a material stream.

With this pre-processed data the actual control algorithm can be realized, e.g., based on threshold transgression, steady adjustment of the measurand allowing for maximal approximation to a target value, or alike. The timeframe in which such adaptations must be induced by the algorithm must be tailored to the application at hand. For example, screen cut changes in an upstream sieve every second based on strongly fluctuating data that is received by the sensor 30 seconds afterwards, cannot be used effectively. Accordingly, moving averages could be applied to smoothen the highly fluctuating volume data and adequate control cycle times would allow for sensible screen cut adaptions.

Despite the aforementioned three main challenges, a comprehensive understanding regarding interdependencies of parameters, target values, and machine requirements for optimal performance are imperative to implement any form of adaptive plant control. Additionally, the costs of any adaptive plant control and its impact/potential must be appropriately interrelated.

4 Case study on adaptive screen cut control

In the following, we present preliminary results from a case study on adaptive screen cut control in a LWP sorting plant. Sensor-based area flow control was implemented in the mid-coarse and mid-fine processing lines during regular operation time. Access to the sorting plant for these trials was provided by the company PreZero.

For data acquisition, two hyperspectral-imaging NIR-sensors (Helios EQ32 [EVK Kerschhaggl GmbH; Raaba, Austria]) operating in the wavelength range of about 1050 nm to 1.700 nm were utilized. Each NIR-sensors measures one acceleration of a sensor-based unit for sorting out beverage cartons in the (i) mid-coarse and (ii) mid-fine processing line, respectively, i.e., the pre-conditioned material flows after air classification and ferrous separation. Based on the classified NIR-data (false-colors) the occupation density, i.e., the area share of the acceleration belt that is occupied with material is calculated, which is directly linked to the area flow (occupied area per time unit).

The movable belt under the drum screen (Fig. 3) was adjusted to various positions to assess the effect of this parameter with regard to the split of the area flow optimally between the mid-coarse and mid-fine processing line. The area flow was chosen as the evaluation criterion, as both processing lines were mostly equipped with optical sorters which in turn classify the material stream based on areal information. Accordingly, the parameter to be adjusted is the screen cut, while the correlating target values are the occupation densities (or area flows) in the downstream processing lines. The chosen belt positions for screen cut adjustments are shown in Fig. 3.

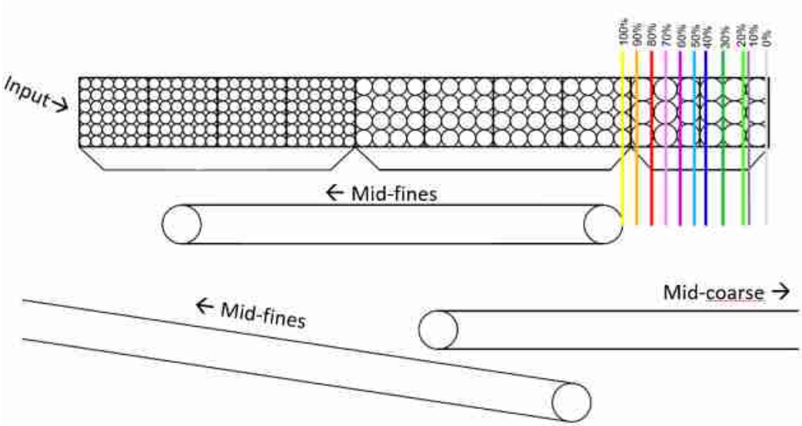

Fig. 3: Positions of moveable conveyor under drum screen for screen cut adaptation between mid-coarse and mid-fines

The occupation density, as monitored by the NIR-sensors, at each position is displayed in Fig. 4. The boxplots (divided in quartiles) illustrate the occupation density fluctuations in each line.

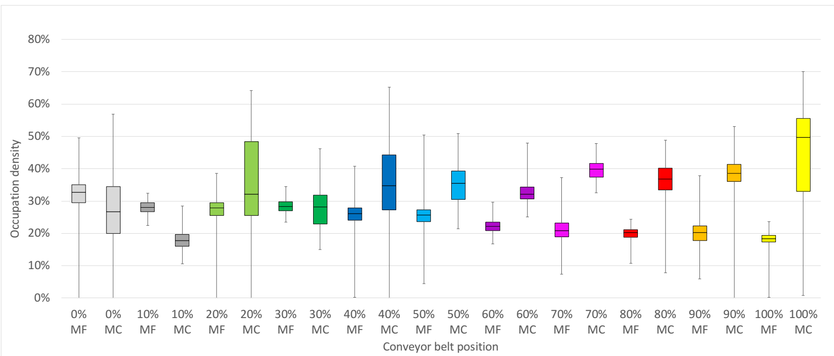

Fig. 4: Occupation density in mid-fine (MF) and mid-coarse (MC) lines in dependence of conveyor belt position (positions in Fig. 3 are colour coded accordingly)

One can see that the occupation densities on both lines differ strongly (on average by 31% - MC: 50% and MF: 19%) difference at conveyor belt position 100%, while the equilibrium (at about 29%) is reached at movable conveyor position 30%. Between positions 100% and 70% no significant change with regard to the occupation densities can be recorded. From positions 70% to 40%, however, noticeable convergence of the occupation densities in both lines (40%→35% in mid-coarse and 21%→27%) can be observed. A steady but slow convergence to equilibrium can be noted between 50% and 20-30% position. Below 20% the occupation densities diverge noticeably.

To assess the impact of this parameter (screen cut) the yield of several product fractions in the heavy line of the plant was measured at position 100% for one month and compared to the yield of those product fractions, when operating at 20% position for one month. Results show significantly improved yield (3 wt% to 15 wt%) for the product fractions generated from the heavy/3D material flows, produced at the 20% position compared to the yield at the 100% position.

Both test phases were conducted in summer, to reduce the effect of changing humidity during these months. However, since the depicted trials were conducted during normal operation of the plant certain external effects (changes in input composition, holiday season, etc.) cannot be fully excluded. During these test months changes were made in the 2D/light processing lines, which is, why neither improvements nor a decline in those processing lines can be traced back to these changes. Nonetheless, it is reasonable to hypothesise that similar effects can be expected in the 2D/light processing lines if the material distribution of these material streams changed equivalently.

It may be assumed that a near real-time adaptive screen cut control would allow even higher improvements in plant performance, as temporal fluctuations could be potentially compensated. Nonetheless, such a control circuit poses a complex challenge in which not only two processing lines of a sorting plant must be observed but rather the effect on all output fractions (yield and purity) should be part of such a function. This is because the focus (purity vs. yield) regarding the sorting algorithms in all optical sorters highly affects what is affected by an adapted screen cut. A fixed prediction regarding the benefit for a process flow can barely be made in advance. Especially as the preceding operation of any plant leaves only a certain potential for improvement.

5 Conclusion

In this paper, the potential and challenges in adaptive plant control for waste sorting plants was discussed. While a multitude of parameters in several pre-processing and sorting machines can be adapted, overlooked high-impact parameters seem to be located in the pre-processing stage of a sorting plant. The accurate adaptation of a sorting plant based on sensor data is subject to the stability and accuracy of sensors and process control algorithm. Prerequisite to all efforts regarding adaptive plant control is comprehensive knowledge regarding the quantitative influence such parameters have for all process lines in a processing plant.

The potential of one high-impact parameter was shown by a case study on adaptive screen cut control. Two NIR-sensors were applied to assess the area flows in two parallel processing lines by means of the detected occupation densities on speed belts. Results show significant improvements of the plant performance in the heavy/3D processing lines: By optimising the screen cut based on the acquired sensor data to achieve even occupation densities in both processing lines, the yield of all 3D product fractions could be increased by 3 wt% to 15 wt%.

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