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RESEARCH ARTICLE

Collection of Plastic Packaging of Various Types: Sorting of Fractions of Plastic Waste Using Both Automated and Manual Modes

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ABSTRACT The efficient use of municipal waste is becoming increasingly important for sustainable environmental quality. An integral part of the process of recycling waste material is its quality sorting. Nowadays, both manual and automated sorting methods, especially optical sorting, are used worldwide for sorting mixed waste. This article presents the application of the NIR/VIS optical sorting system through a description of this processing equipment integrated into a specific plastic waste processing line. The aim of the article was to select the optimal mode of operation generally applicable to mixed waste, and, specifically, to compare the quality of sorting of plastic waste in automated and manual sorting modes. In order to compare the efficiency of the sorting system, significant parameters of the sorting process were proposed. The measurement of the plastic waste sorting purity parameter was based on data obtained by weighing selected control samples, and the evaluation of the results of these measurements showed, in particular, the dependence of the concerned parameter not only on the sorting mode, i.e., automated and manual, but also on the conveyor belt speed/waste material flow, on the pre-sorting methods and, in the case of manual sorting, on the operating shift. The subsequent economic assessment of both sorting processes clearly declared the investment in automated sorting systems in the optical system operation mode not only as profitable, but also as extremely advantageous both for the production economy and the environment.

INDEX TERMS Municipal plastic waste, manual and automated sorting, optical sorting equipment, processing parameters, operation mode economy.

I. INTRODUCTION

Environmental protection is currently one of the priority issues, the seriousness of which transcends regional and national boundaries. New knowledge in waste management, particularly from the construction of landfills and incinerators, points to the need to tackle a major problem with increasing consumption, namely the reduction of waste accumulated from mining, industry and agriculture. Automation, collection logistics, waste concentration, and recycling are

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playing an increasingly important role in the waste management system [1], [2].

In the issue of current waste technologies, the extreme durability of plastics must be emphasised in the context of increasing environmental pollution. The reuse of this specific material, which can be reused or recycled, is, therefore, highly promising and desirable. Recycling after waste sorting maximises the amount of plastic waste that can be recovered and then used to produce high-quality, consistent recycled material competitive with virgin plastic [3], [4].

In addition to the laws currently in force and forthcoming legislation, technical and economic instruments must be promoted and continuously applied to strengthen the prevention of waste growth and the recovery of recycled waste [5], [6].

Rapid urbanisation and industrialisation are causing an extreme increase in the production of mixed solid waste, and, in particular, municipal plastic waste unevenly and globally. Solid waste can come from the manufacturing process or from products after they have been used in the commercial, industrial, construction, and domestic sectors [7]. Countries with a relatively higher gross domestic product tend to produce significantly more landfill waste. Statistical trends predict that the production of solid and plastic waste in the world's metropolitan areas will increase from 1.3 billion tonnes in 2012 to 2.2 billion tonnes by 2025 [8], [9], [10], [11].

Waste prevention is a long-established way to reduce waste most effectively. However, when waste is generated, it must be treated and used in a thoughtful way. The basic step in the treatment process is pre-sorting the waste after it has been collected from the consumer and then sorting it for treatment. Currently, two basic waste sorting systems are applied, namely the traditional manual system and a modern automated system using optical detection to sort the waste material. While the advantage of manual sorting over the automated system is the lower initial investment, the disadvantage is the considerable limitation in terms of sorting the different types of waste and managing the large waste capacity [10], [12].

It is relatively easy for robots to discriminate between different objects but programming them to discriminate between different materials is much more difficult. Combining sensed data with real video footage from robot cameras seems very promising in current practice, which increases the accuracy and reliability of sorting in detecting different types of waste materials. Various automated recycling centres nowadays use mainly optical (for plastic detection), magnetic (for iron and steel detection) and eddy current (for aluminium and non-magnetic metals detection) sorting systems. In current practice, several sorting systems are used for sorting municipal plastic waste, depending on the sorting method or the characteristics of the waste material, e.g., flotation, air separation, laser, roentgen, camera systems, etc. [13], [14].

The most widespread and most advanced waste sorting system worldwide is the optical separation method, which works Based on artificial lighting of the waste material flow, detection by sensitive sensors, and a pneumatic ejection of the detected material into a designated position (into a collection bin under a conveyor belt, a passive chamber or a textile bag). Nowadays, automated sorting of waste on the conveyor belt is most often represented by an optical scanning system with NIR/VIS scanning detectors, which is connected to a pneumatic system of air nozzles to launch the detected material [15], [16], [17].

The NIR (Near InfraRed Reflection) sensor emits infrared radiation with a wavelength of 760 to 2,500 nm. The reflection of this radiation depends on the chemical composition of the material being sensed [18].

The VIS (Visual Spectroscopy) sensor detects material in the visible region of electromagnetic waves, i.e. in the wavelength range of 390 to 760 nm. Since the reflection of this wave depends on the colour of the object being scanned, the sensor is applied for the detection and sorting of bottles made of thermoplastic polyethylene terephthalate (PET) and polyethylene (PE). In principle, it is an improvement on the conventional RGB (Red-Green-Blue) camera technology, which is able to capture a stronger signal of all spectral colours and, consequently, improve the quality of the sorting of plastics [19].

The captured reflected NIR/VIS radiation is transmitted to special software for processing, which creates a 2D image of the detected object at high speed, detecting not only its material and colour but also its size, shape, and position. The software also controls the pneumatic part of the device with air nozzles that eject the detected plastic from the waste material flow on the conveyor belt with precisely targeted airflows. The precise detection of this technology ensures high post-sort purity (90 to 98%) and a sorting capacity of up to 10 tonnes per hour.

The identification and subsequent sorting of waste can also be very accurately carried out using the LIBS method, an analytical chemical method based on the principle of atomic emission spectrometry. This method is based on the interaction of a laser pulse with the surface of the material to be tested, during which the energy delivered vaporises (ablates) a small amount of the material to form a luminous plasma whose radiation contains the spectral lines of the vaporised elements. For the identification of plastic waste, this method is specifically applied as the LIPS (Laser Induced Plasma Spectroscopy) method. The system can identify various plastics, such as, in particular, high-density polyethylene (HDPE), low-density polyethylene (LPDE), polypropylenes (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), based on the ratio of the intensities of the carbon and hydrogen (C/H) elements present [20].

Following the application of the LIPS method, a compact and reliable method was proposed for the instantaneous classification of different types of plastic particles using statistical analysis, such as linear and value correlations. Spectra from plastics are collected, monitored and compared with reference libraries [21], [22].

FIGURE 1. The principle of reflection detection of electromagnetic beams detected by scanners.

In conclusion, it can be stated that for all known applied methods of waste material management (recycling, incineration-cogeneration, chemical-physical or biological disposal, landfill), sorting is not only advantageous but necessary so that especially plastic waste does not end up unnecessarily in landfills, incinerators or cement plants. An automated sorting line is unquestionably a fast and reliable way to an efficient circular economy. Given the combination of scanning, evaluation, and ejection processes of sorted waste into a targeted area, this technology is now becoming an indispensable separation method with high purity of sorted plastic, speed and reliability of operation.

II. MATERIALS AND METHODS

The first step of the research was to set up technological and process options for detecting and evaluating significant parameters of selected forms of municipal waste from a technological point of view. The actual sorting process of plastic waste is implemented at the end of the transport route, where the waste material is separated into well-sorted plastic and imperfectly sorted waste, with both types of material ending up in separate bins. The well-sorted plastic waste contains the desired clean plastic and unwanted contamination, while the imperfectly sorted waste contains lost plastic and residual waste.

Optical waste detection and separation technology consist of two parts, namely, a sensing system and an actuator. The sensing system emits electromagnetic radiation on the waste material flow, whereby the radiation is partly absorbed by the material and partly reflected back to the sensor. The waste material is categorised based on the adsorption of radiation into categories according to the sensors used, i.e. NIR/VIS sensors (Fig. 1). Once the plastic waste is detected, the air nozzle of the actuator performs its physical separation from the waste stream.

The efficiency of this technology is mainly based on the selection of a suitable sensor based on the reflectivity and colour of the sorted waste material. Due to the higher inhomogeneity of the sorted mixture, it is advisable to choose a sensor with a high wavelength range. Another important parameter to be selected is the material transport speed under the sensor, which must not be too high with respect to the sorting quality; therefore, an optimum value must be found and set. With an air classifier, the sorted material can also be separated into light and heavy fractions, the principle being to mix the airflow with the sorted material. The hoppers and conveyors for the outgoing sorted material must be suitably positioned so that the material does not fall to the ground outside the conveyor belt.

In addition to the operational data, the process of design and selection of the technological solution by the supplier and the plant operator is also presented. The sorting system is also described, which provides a source of operational data for both manual and automated modes for testing purposes.

A. THE DESIGN OF THE TECHNOLOGICAL SOLUTION FOR THE SORTING SYSTEM

Today's demanding market mostly requires the application of complex and efficient solutions, so with regard to customer requirements, the following is monitored:

- covering the required waste treatment capacity,
- ensuring knowledge of the morphology of the waste being treated,
- setting the best available technology in terms of process sustainability,
- ensuring the economics of the project setup is in accordance with the applicable legislation.

The first very important stage is elaborating the technical process specification, which defines what the customer expects from the sorting technology. The process results in the definition of the main parameters, which are verified in operation when the process line is handed over to the customer and then evaluated. The preparation of the technical process specification takes a minimum of two to three months and consists of many meetings, processing site inspections, as well as many analyses, including initial technical design options.

After the technical process specification is developed, the technological solution is prepared. Once the technical specification with the design of the main process parameters has been agreed upon, it is important to prepare a detailed quotation and, after its approval by the customer, to enter the precisely defined technical requirements of the process directly into the contract with a clearly formulated delivery of the interface and the setting of the required parameters in the delivery. This document is then the basis for a proposal for customer approval. In the preparation phase, the main operation of the sorting line is then processed in the form of a mass flow diagram. According to this diagram, the transport channels for the processed waste are calculated and set, and the processing capacity of the sorting line is also set.

After setting up the process design of the sorting line, the processing equipment is designed and specified with a detailed technical description, including the calculation of the electrical power requirements. The power consumption parameter is important for the customer as it determines the connected power of the electrical installation. This part of the preparation has to be declared in advance, as it may represent an additional investment in the re-wiring of the existing plant. Once the above requirements have been fine-tuned and other possible space needs have been addressed, the drawings for the production needs are prepared by the supplier.

The issue of possible non-compliance with the main process parameters is verified Based on testing the main parameters of the line in test and actual operation, where the following parameters are tested:

- the flow rate of the main process line – capacity of the sorting line ($t{\cdot}hod^{-1}$),
- sorting quality – efficiency of the sorting process (%), net sorted and lost plasma waste (%),
- mechanical functionality, the functionality of main and safety control of mainline circuits,
- total electrical power of the line (kW),
- automation of the entire sorting process,
- any other requirements of the institutions concerned.

B. SORTING LINE FUNCTIONALITY

The functionality of the processing sorting line can be evaluated from a mechanical, control and safety point of view. Testing of other parameters is usually carried out at the same time as monitoring the functionality of the line, namely the measurement of the line flow and the quality of the sorting of the waste material.

In order to determine the mechanical functionality of the sorting line, its operation is monitored and analysed for 72 hours without any mode changes and without interruption, or one or two changes of the continuous operation mode are checked based on agreement with the customer, and the test is completed by simulating the response of the parent system by a randomly selected electrical protection (e.g. by pulling the safety button).

The main reasons for not achieving the desired functionality and reliability of the operation of the proposed sorting line are mainly:

- poor concept of the sorting line (layout during design),
- faulty mechanical assembly,
- incorrect connection of the electrical wire,
- incorrectly programmed automatic line control equipment,
- other malfunction (staff error, power failure, etc.).

In order to determine the functionality of the control and safety circuits of the sorting line, the line states that may actually occur in certain situations are simulated; in particular, the signalling of selected safety circuits and all emergency buttons are tested. At the end of the testing, one of the states is selected, the sorting line is stopped, and its control operation is evaluated.

The main causes of failure of the desired control functionality and operational safety of the proposed sorting line, e.g. malfunction of the monitored system of the machine unit, are mainly:

- faulty or incomplete wiring, faulty electrical installation,
- poorly programmed automatic line control,
- other malfunction (staff error, power failure, etc.).

C. DESCRIPTION OF THE SELECTED SORTING SYSTEM

The NIR/VIS technology was used for waste sorting in the framework of a technological sorting line for the processing of plastic waste at the centre of OLO, a.s. (Odvoz a likvidácia odpadu, a.s.) in Bratislava, Slovakia.

These technologies work on the principle of transmitting and receiving electromagnetic waves at scanning rates of up to 320 points per second. The two systems that the test line was equipped with, and from which the operational information obtained from the testing was used, were installed on 1,400- and 2,000-mm wide equipment in the plastic waste and recovered paper sorting centre (Fig. 2). The NIR/VIS optical detection system (Fig. 3) was installed on optical units of the Autosort machines of Tomra Sorting Solutions (Norway), owned by OLO.

In order to improve the distribution and layering of waste, the incoming mixed waste is fed evenly onto the conveyor belt via an unpacker, drum vibrating screen and separators. The ballistic separation separates the waste into 2D parts (bags or films) and 3D parts such as cups, trays, or cans. The technology includes a magnetic separator for ferrous metals and an induction separator for the collection of non-ferrous metals, as a result of which the sorting line also effectively pre-sorts various metal packaging. Due to the frequent contamination of plastic waste, a sensor working Based on electromagnetic field generation in ferromagnetic parts commonly found in the overall waste material stream can be placed in the conveyor body to detect metal parts.

At the end of the conveyor belt path, the waste material is finally detected as plastic waste by the sensing unit of the sorting machine. The scanner detects the waste material

FIGURE 2. The complete sorting line in the production hall.

FIGURE 3. Line with NIR/VIS optical sorting system.

objects and then commands the control box with an output signal to start ejecting (blowing) the detected waste material parts with the air nozzles (located on the valve block at the end of the conveyor belt). The sorted material is lifted by air through the separation roller inside the separation chamber and ends up in the separation bin. The rest of the waste material falls onto the lower conveyor belt or also into the hopper. Figure 4 shows a schematic of the process of firing the detected waste type (plastic) with compressed air through calibrated perforated nozzles located in the ejector bar across the width of the belt. Figure 5 shows the sorted waste output from the sorting line.

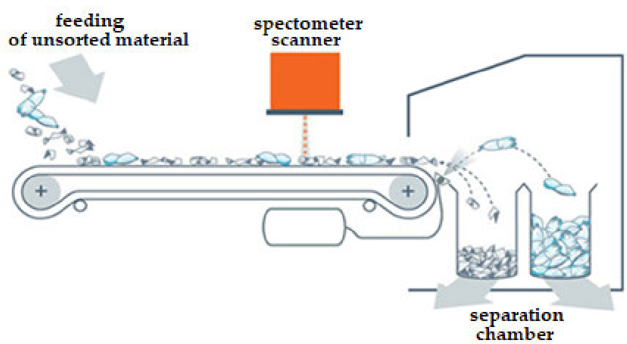

FIGURE 4. Schematic of the detection and ejection of plastic waste on the NIR/VIS optical sorting system.

D. PROPOSED SORTING QUALITY PARAMETERS

The quality of the sorting process of plastic waste can be objectively quantified mainly by means of three significant parameters, namely the capacity of the sorting cycle of the processing line, the coefficient of purity of sorting waste plastic and the coefficient of loss of waste plastic due to imperfect sorting.

The flow of processed waste quantified by the parameter of sorting cycle capacity is one of the key parameters of waste material sorting, which is important for the customer not only in terms of the need to process the total required capacity of waste material but is also significant in terms of the direct impact on the economy of the sorting line operation.

The production capacity of the processing sorting line is mainly influenced by the setting of the conveyor belt speed, i.e., the flow of waste material. Possible causes of the non-compliant value of the parameter in question may be:

FIGURE 5. Schematic of the detection and ejection of plastic waste on the NIR/VIS optical sorting system.

- incorrect flow calculation/incorrect width of transport routes,
- improperly designed engine speed transmission,
- incorrect installation of the technology (possible collision of installed equipment on transport routes, protruding parts of oversized waste material, etc.).

The measurement of the value of the concerned parameter is carried out by weighing the sorted/processed plastic waste for a given production time. In production, the production capacity of the waste material sorting process is declared in tonnes per hour, while for the testing of selected samples, units are converted to kilograms per minute using (1).

$$Q = \sum\nolimits_{i=1}^{n} \frac{m_i \cdot t}{60} \tag{1}$$

where Q is the production capacity of the processing line, m_i is the weight of the processed waste material in one cycle, t is the processing time of the waste material in one cycle, and n is the total number of production cycles.

The quality of the plastic waste sorting process is the basic parameter of the sorting line efficiency in separating waste material by optical heads, which is given as a technical ratio quantity in percentage. The parameter in question represents the efficiency of the sorting process, and its value in technical practice ranges typically from 90 to 98 %.

The sorting purity coefficient is influenced not only by the relevant components of the mixed waste but also directly in the processing process, especially by the conveyor belt speed setting, especially in the case of manual waste material processing. Possible causes of an unsatisfactory value of the parameter in question may be:

- insufficient quality of the sorting system (detectors, ejectors, transport and control system),
- significant contamination of waste with impurities,
- the presence of oversized and undersized waste in the sorting line,
- overloading of the waste material flow,
- incorrect layering of sorted plastic waste under optical heads,
- incorrect classification adjustment for the sorting program,
- conveyor belt speed (conveyor motor) malfunction.

The measurement of the concerned parameter value was carried out by capturing (manually selecting the contamination) and weighing the selected measurement sample and then evaluated according to (2),

$$\eta_C = \frac{m_C}{m_C + m_K} \tag{2}$$

where are: η_C sorting purity coefficient (Clear) for plastic waste (%), m_C weight of well-sorted clean plastic compressed into a plastic ''box'' (kg), m_K weight of contamination (K-contamination) (kg).

Theoretically, the quality of sorting can also be defined using an additional parameter for contamination of well-sorted waste, namely the η_K (%) plastic waste contamination coefficient (3):

$$\eta_K = \frac{m_K}{m_C + m_K} \wedge \eta_C + \eta_K = 100\% \tag{3}$$

For the customer, it is important to monitor both the quality of well-sorted waste material and waste material lost during an imperfect sorting process. In this case, it is plastic waste not captured by the optical scanners ending up in the residual waste stream quite unnecessarily. For the customer, however, it represents a loss of profit, the price at which the lost waste could have been sold on the market. Possible reasons for the concerned non-compliant value of the parameter could be:

- incorrectly set sorting program,
- insufficient quality of the sorting system (detectors, ejectors, transport, and control system),
- the level of waste pollution,
- the presence of excessive and undersized fractions in the waste stream,
- overloading of the mass flow during the sorting process,
- incorrect layering of sorted material under the scanning head,
- inadequate transport speed.

In particular, when imperfect waste sorting is visually and continuously monitored, it is necessary to test its quality objectively and accurately in order to analyse the causes in a comprehensive manner. The measurement of the parameter in question is carried out by capturing (manually selecting uncaptured plastic), weighing the selected measurement sample at the outlet of the processed waste stream from the conveyor belt, and evaluating it by calculation according to (4),

$$h_L = \frac{m_L}{m_L + m_R} \tag{4}$$

where h_L is the coefficient of loss of plastic waste (%), m_L weight of lost plastic waste (kg), m_R weight of the remaining waste material in the weight of the selected sample (kg).

Theoretically, the quality of sorting can also be defined using an additional parameter for residual waste material, namely the h_R (%) residual waste coefficient (5).

$$h_R = \frac{m_R}{m_L + m_R} \tag{5}$$

FIGURE 6. **Tested waste material before entering the sorting line.**

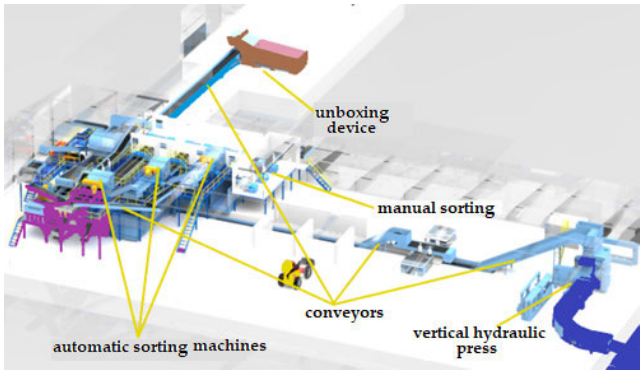

FIGURE 7. **Schematic of the tested sorting line layout.**

In practice, the most useful and most common of the four possible sorting quality parameters presented is the parameter of the purity of sorting of plastic waste, measured and evaluated when testing selected samples to determine the efficiency of processing plastic waste by sorting. Its mean value $\bar{a}$ for repeated manual sorting from a set of n measurements ($n = 5$) is the arithmetic mean (6), where a_i is the sub-measurement.

$$\bar{a} = \frac{\sum_{i=1}^{n} a_i}{n} \tag{6}$$

Chapter III. of the article presents an example of testing the efficiency of a sorting line when changing the waste material sorting method, conveyor speed, and the flow rate of processed waste material from 1.5 to 3 t·hod^{-1}.

III. METHOD OF IMPLEMENTATION OF WASTE MATERIAL SORTING

The main parameters of the sorting process need to be defined, quantified, evaluated, and then verified so that they can be correctly applied in the processing process to give the operator the best possible operational setup with the required parameters in the specified modes of line operation. Only such a state then results not only in the optimisation of the technical lifetime of the machinery but also in the desired economic benefits.

A. THE DESCRIPTION OF THE SITE AND WASTE MATERIAL SORTING METHOD

The measurements were carried out on the re-sorting line directly at the operator of the plastic waste re-sorting line in Bratislava after 800 hours of pilot operation. The sorting line was cleaned prior to the measurements in order to eliminate the effects of inaccuracies in the sorting conditions. The ambient temperature was 18 °C. The prepared municipal plastic waste was dry, loose, and stored for entry into the facility for sorting. Figure 6 shows the plastic waste that was used to measure selected line parameters at the set modes.

The actual sorting line consisted of 54 technological devices, including 4 separate optical sorters 2 × 2,000 mm and 2 × 1,400 mm wide. On one 2,000 mm wide optical sorter, only clear film is sorted as standard Based on visible light detection, which has already been sorted by weight on a special machine, the ballistic separator. The separator operates on the gravity principle of an inclined plate with parallel capture of its sub-sieve fraction (small waste elements of less than 50 mm in size).

Other heavier plastics are sorted on NIR/VIS two-way optical sorting machines of the 1 × Autosort 2000 and 2 × Autosort 1400 type. A total of 7 types of materials are sorted on all four optical sorting machines:

- transparent foil,
- PET (polyethyentetraphtalate) transparent colour,
- PET blue colour,
- PET green colour,
- PET mix other colours,
- HDPE-PE (high-dense polyethylene and polyethylene),
- PP-PS (polypropylene and polystyrene).

In addition, three other commodities that are not sorted by the optical sorting line are sorted on these optical sorting devices:

- iron material (Fe),
- non-ferrous material (Al, Cu, etc.),
- undersized material (fraction less than 50 mm).

Figure 7 shows a schematic of a complete sorting line with the machinery involved in the sorting cycle testing.

B. THE DESCRIPTION OF THE WASTE MATERIAL FLOW IN THE SORTING PROCESS

The processing of the waste material flow is described continuously in the sub-process stages implemented as preparation and delivery of plastic waste, as well as the set modes for measuring sorting parameters and a description of the measurement conditions.

The incoming plastic waste is transported and emptied by the handling equipment into the unpacking facility. The treated plastic waste continues by direct conveyor belt to the collection and distribution hub for further processing.

Preparation of waste through Channel I.

As part of the preparation of waste for the treatment process, waste is taken to the ballistic separator for the separation of light packaging materials (foil), hard packaging, and unusable inert waste (small "sub-sieve" fractions), which will be

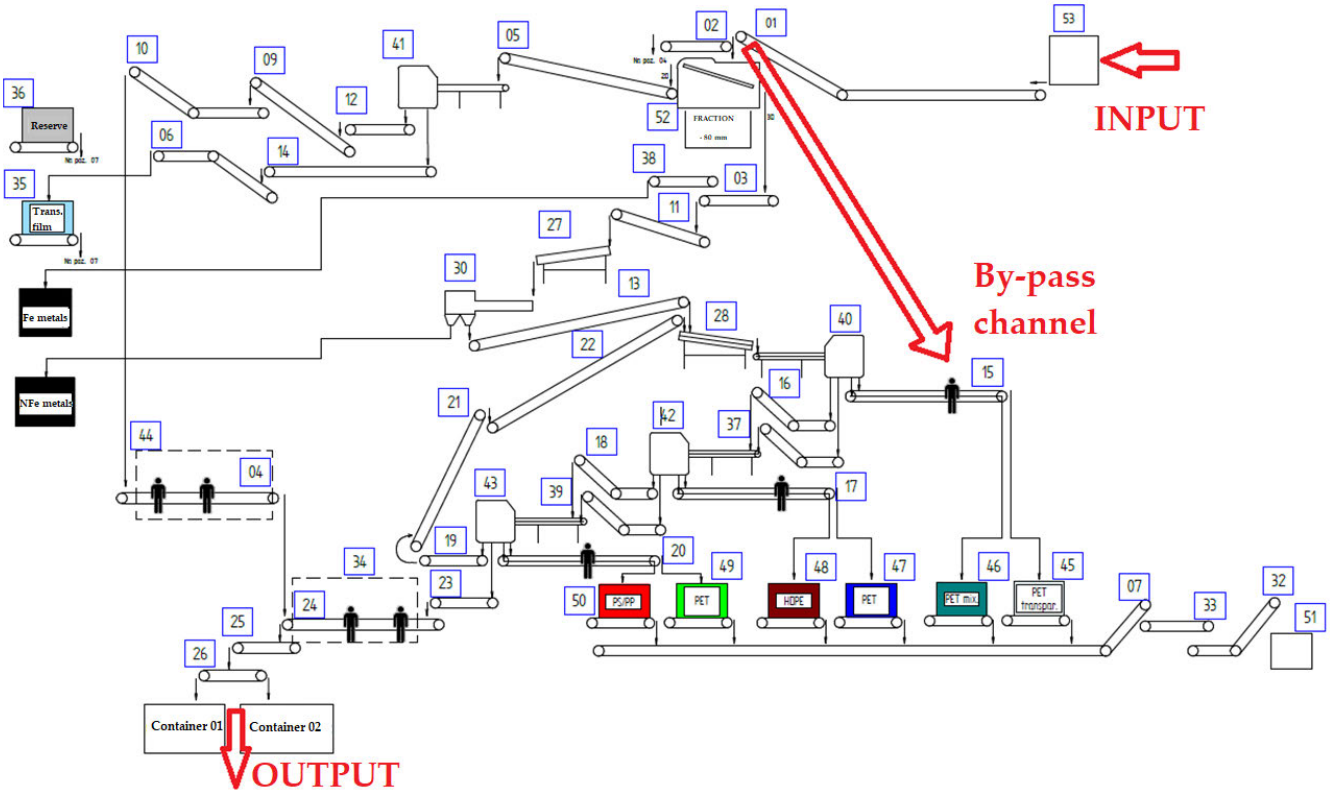

FIGURE 8. Technological diagram of the test sorting line.

taken out in a newly created side opening of the production hall.

Sorting of light waste fractions through channel II.

The light packaging fraction (light plastic film) of the waste proceeds by conveyor to a workstation with two operators to remove oversized light packaging (film). The waste stream continues to the NIR/VIS optical sorting plant for sorting transparent films. The flow of the coloured film and other admixtures continues through conveyors for manual sorting. The sorted light transparent waste proceeds via conveyors to a moving bottom hopper; after confirmation of the operator's command, it proceeds via the conveyor to the baler for baling and subsequent dispatch or to the warehouse.

Sorting of solid waste fractions through Channel III.

The heavy waste fraction (hard plastic) sorted by the ballistic separator falls onto the weigh conveyor. At this stage, metal is also sorted by magnetic separators, which fall into a mobile container. Next, the hard plastic is conveyed via a vibrating conveyor to a non-magnetic metal separator operating Based on magnetisation of non-ferromagnetic material by means of eddy currents. The non-metallic material is transferred to an optical separator for the automated separation of hard PET polymers. The incoming material enters the plant through a split belt, where automated separation of selected plastics takes place. The selected plastics go through a conveyor into a moving bottom box.

The remainder of the waste is further processed into a second split belt optical separator where automated separation of the plastics takes place, separating the coloured PET blue. These plastics then go through a conveyor to another moving bottom box. The remainder goes on to a third split belt optical sorter for further processing, where the plastics are automatically separated, and HDPE (high-density polyethylene or high-density polyethylene) is separated and left in the box. The remainder of the waste material proceeds via conveyors to a second sorting lane on the second belt of the first NIR/VIS optical sorting plant. Here, the automatic separation of the other hard plastics takes place, where the green PET is separated into the moving bottom box, and the remainder continues for further processing to the second channel of the second optical NIR/VIS sorting machine, where the automatic separation continues, and the remaining mixture of other PET is separated into the moving bottom box. The remainder of the waste proceeds to the second channel of the third optical NIR/VIS sorting, where the plastic mixture of PE (polyethylene) and PP (polypropylene) is separated, again continuing into its moving bottom box.

For each of the three optical facilities mentioned above, manual sorting of the waste material is carried out to achieve 100% clean sorting. Unsorted waste from the second sorting cycle at the optical plant is again manually sorted, where waste not captured by the sorting process can be found and sorted. If necessary, the heads of the NIR/VIS optical equipment can be rearranged so that they can be sorted in a different order, or the settings can be changed for different types of sorted materials.

Manual separation of plastic waste through the by-pass channel.

In case of a failure in one of the technological equipment of the automated sorting line, a separate channel for manual waste processing is designed, located in the manual sorting booth with the use of personnel (service capacity is limited for time up to half an hour and for ten employees). Figure 8 shows the process flow diagram of the whole sorting line, on which the main separation parameters were measured during the period of interest and in the set operating modes.

The sorting line is operated in two working shifts for 24 hours, i.e., the first shift lasts from 6:00 a.m. to 6:00 p.m., and the second shift lasts from 6:00 p.m. to 6:00 a.m. Waste is processed in the same way during both shifts. The material is manually pre-sorted before entering the first sorting plant (ballistic separator for separating packaging and hard plastics) by selecting oversized materials (objects larger than 500 mm), which may cause not only possible blockage of the waste material flow but also deterioration of the sorting quality.

In the automated mode, the operator manually sorts the oversized material at the conveyor belt at 70 % of the optimum conveyor belt speed/waste material flow setting. Only pre-sorted waste material then enters the sorting line on the conveyor belt.

The basic process parameters of the sorting cycle that affect the overall economy, performance, and quality of the processing process are:

- the capacity of the sorting cycle, expressing the quantity of the waste flow to be processed in units of $t{\cdot}hod^{-1}$ in production or in $kg{\cdot}hod^{-1}$ when testing a selected sample of waste material, according to (1) and in relation to the set processing mode, in particular, the conveyor speed,
- the sorting purity coefficient of the sorting of plastic waste expressing the efficiency of the sorting process in relative percentage, according to (2),
- the coefficient of loss of plastic waste by imperfect sorting, according to (4).

If the operator of the sorting line does not currently achieve satisfactory results in accordance with the desired process parameters, then the sorted commodity is sold on the market below the desired price or not at all. From a market perspective, the desired parameter is, therefore, the quality of the sorting of the waste material, represented by purity of the sorted waste greater than 95 % at the maximum processed capacity. This quality requirement applies to both automated sorting and manual sorting, which is present on the line in the sorting cabin and becomes active if there is a problem on the automated part of the sorting line.

Measurement of selected samples of waste material took place at two locations, namely in the automated part of the sorting line by removing them from the output baskets and in the manual part of the sorting line (sorting box) used for sorting in case of technical failure on the automated part of the sorting line. In the manual mode, only the visible commodities were sorted: PET clear, PET blue, PET green, and PET other (mix).

For the automated sorting mode, six conveyor belt speeds were used, namely:

- $3.2\ m{\cdot}s^{-1}$ corresponding to the maximum, i.e., 100% of the conveyor speed,
- $2.88\ m{\cdot}s^{-1}$ corresponding to 90 % of the conveyor speed,
- $2.56\ m{\cdot}s^{-1}$ corresponding to 80 % of the conveyor speed,
- $2.24\ m{\cdot}s^{-1}$ corresponding to 70 % of the conveyor speed,
- $1.92\ m{\cdot}s^{-1}$ corresponding to 60 % of the conveyor speed,
- $1.60\ m{\cdot}s^{-1}$ corresponding to 50 % of the conveyor speed.

For the manual sorting mode, a lower speed setting was used due to the limited responsiveness of the workers to capture positive sorted material:

- $1.20\ m{\cdot}s^{-1}$ corresponding to 40 % of the conveyor speed,
- $1.08\ m{\cdot}s^{-1}$ corresponding to 36 % of the conveyor speed,
- $0.96\ m{\cdot}s^{-1}$ corresponding to 32 % of the conveyor speed,
- $0.84\ m{\cdot}s^{-1}$ corresponding to 28 % of the conveyor speed,
- $0.72\ m{\cdot}s^{-1}$ corresponding to 24 % of the conveyor speed,
- $0.60\ m{\cdot}s^{-1}$ corresponding to 20% of the conveyor speed.

To analyse the results of the measurement of process parameters on the selected sorting line, the measurement of the sorting purity coefficient as a function of the change in processing mode was used.

Testing and trend analysis of the dependence of the sorting purity coefficient on the capacity of the sorting cycle was carried out on the sorting line directly in the premises of the customer processing pre-sorted municipal plastic waste of standard composition and preferentially focuses on the separation of PET material of all colours and other hard plastics and foils.

At the set waste material flow rates, samples of the selected PET paint were taken into a pre-weighed plastic box for:

- automated mode, after each sorting process by NIR/VIS,
- manual mode on the outfeed conveyor in the sorting cab.

In addition, five partial measurements and evaluation of the quality coefficient of the purity of the sorting of the collected samples for each selected mode were performed by weighing on calibrated digital scales. Thus, a total of 5 × 6 partial

FIGURE 9. Digital scales used to measure plastic waste samples.

measurements were made for each combination of parameters (for day and night shifts, with and without removal of oversized material, for automated and manual mode):

A) day shift with oversized waste collection at the input to the line/automated mode,

B) day shift with oversized waste collection at the input to the line/manual mode,

C) daily shift without oversized waste collection at the input to the line/automated mode,

D) day shift without oversized waste collection at the input to the line/manual mode,

E) night shift with oversized waste collection at the input to the line/manual mode,

F) night shift without oversized waste collection at the input to the line/manual mode.

Samples of plastic waste were weighed on a benchtop digital technological scale DIBAL PS-50 15/25 kg (Fig. 9), whose uncertainty of the measurement result is declared by the manufacturer due to the used measuring range: 3 kg/1 g; 6 kg/2 g; 15 kg/5 g.

During the measurements, the material was detected in the measured samples that the NIR/VIS sorting systems could not detect because it:

- contained "multi-layered waste",
- was black in colour (undetectable for VIS sensors of the optical sorting system),
- moved (e.g. a full or inflated PET bottle rotated, i.e. changed its position rapidly during scanning),
- there was a random phenomenon of incorrect selection or occasional clumping of material along the route.

The speed of the waste material flow was varied in the control system by a central speed controller of the conveyors (including the conveyor in front of the NIR/VIS optical devices). The lowest speed on the conveyors is set at 50 % in production, as below this value, the operation of the line is economically inefficient, and the motors are subjected to higher loads due to poor cooling, especially in the summer months. The input conveyor drive speed was, therefore, only reduced briefly when testing manual operation modes.

IV. MEASUREMENT RESULTS IN SELECTED MODES

For each mode (A to F), the results of the measurements were recorded in tables and graphs so that their predictive value could be interpreted. The sorting quality coefficient was evaluated according to (2), i.e. as η_C sorting purity coefficient of sorted plastic waste (%).

TABLE 1. Measurement results for regime A.

Flow Speed ($m{\cdot}s^{-1}$)	Sorting Purity (%)	Difference (%)
1.60	96.30	-0.35
1.92	95.99	-0.04
2.24	95.54	0.41
2.56	95.73	0.22
2.88	95.99	-0.04
3.20	96.15	-0.20
	95.95	

Logically and empirically, it can be predicted that the purity of the sorted waste will decrease non-linearly with increasing conveyor speed, both in manual and automated modes.

In the manual mode, the human factor is a significant limitation, i.e. better results can only be expected at lower conveyor speeds, in the day shift, and with oversized material removal. Therefore, for the four modes (B, D, E, F), the measurements for each conveyor speed were repeated five times, and the mean values of the measurements were declared. The data set of manual measurements contained (for four modes, six conveyor speeds, and five repetitions of measurements for each speed) 120 partial indirect measurements of the sorting purity coefficient.

In the automated mode, the technological factor is a significant limitation, i.e. better results can be expected with high-resolution optical sensors and oversized material removal. At the same time, day or night operation plays no role for the machine. The technological factor also concerns the compatibility of the selected equipment since the manufacturer of the optical sorter guarantees the extreme stability of the sorting of waste material by adjustable/recommended conveyor speeds when the optical head is installed correctly but does not assume the setting of extreme conveyor speeds. The automated measurement dataset contained 12 sub-measurements of the sorting purity coefficient (for A and C modes, six conveyor speeds, and unrepeated measurements at each speed).

A. DAY SHIFT WITH OVERSIZED WASTE COLLECTION AT THE INPUT TO THE LINE/AUTOMATED MODE

Based on the measurement results (Table 1, Fig. 10), it can be stated that the sorting purity coefficient appeared to be extremely stable at the selected conveyor speeds, with a mean value of 95.95 %, while this value was within a relatively narrow interval of 0.76 %.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5, using (7), with the tightness of

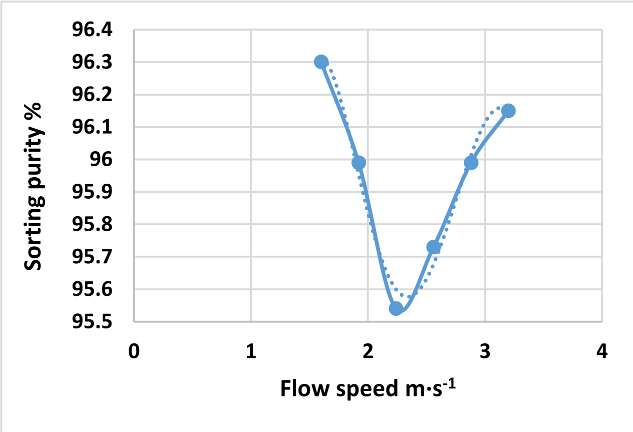

FIGURE 10. Measurement results for regime A.

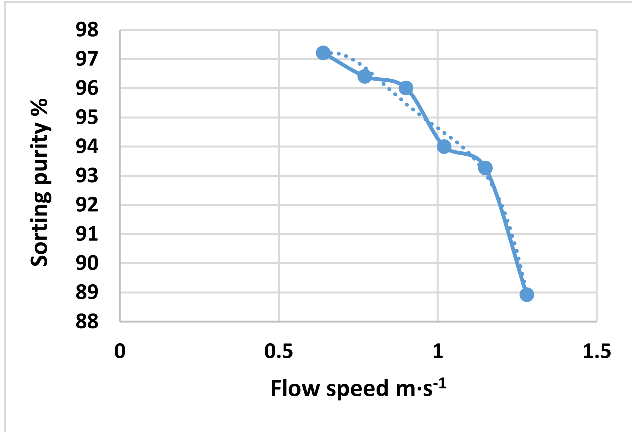

FIGURE 11. Measurement results for regime B.

TABLE 2. Measurement results for regime B.

Flow Speed ($m \cdot s^{-1}$)	Sorting Purity (%)	Difference (%)
0.64	97.21	-2.91
0.77	96.41	-2.11
0.90	96.01	1.71
1.02	94.00	0.30
1.15	93.27	-1.03
1.28	88.92	-5.38
	94.30	

TABLE 3. Measurement results for regime C.

Flow Speed ($m \cdot s^{-1}$)	Sorting Purity (%)	Difference (%)
1.60	95.16	-0.37
1.92	94.85	-0.06
2.24	94.43	0.36
2.56	94.63	0.16
2.88	94.81	-0.02
3.20	94.87	-0.08
	94.79	

agreement between the real and approximated measurement results $R^2 = 0.9786$,

$$\eta_C = 0.7946 \cdot x^5 - 11.315 \cdot x^4 + 61.768 \cdot x^3 - 161.38 \cdot x^2 + 201.41 \cdot x \quad (7)$$

where η_C is the sorting purity coefficient and x is the set conveyor speed.

In conclusion, it can be assumed that repeated automated measurements of Mode A will produce analogous results, i.e. the mean value of the sorting purity coefficient of sorted plastic waste will oscillate around the value of 96 % within an interval of less than 1 %.

B. DAY SHIFT WITH OVERSIZED WASTE COLLECTION AT THE INPUT TO THE LINE/MANUAL MODE

Based on the measurement results (Table 2, Fig. 11), it can be stated that the sorting purity coefficient clearly decreased at the selected conveyor speeds, with a significant decrease at the highest conveyor speed.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5 employing (8), with the tightness of agreement between the real and approximated measurement results $R^2 = 0.9858$.

$$\eta_C = -92.066 \cdot x^5 + 187.02 \cdot x^4 + 94.491 \cdot x^3 + 484.19 \cdot x^2 + 389.38 \cdot x \quad (8)$$

where η_C is the sorting purity coefficient and x is the set conveyor speed.

In the manual measurements of mode B, the value of the sorting purity coefficient was gradually reduced by 8.29 % as the conveyor speed increased.

C. DAY SHIFT WITHOUT OVERSIZED WASTE COLLECTION AT THE INLET OF THE LINE/AUTOMATED MODE

Based on the measurement results (Table 3, Fig. 12), it can be stated that the sorting purity coefficient again appeared extremely stable at the selected conveyor speeds, with a mean value of 94.79 %, with an interval width of 0.73 %. As no oversized material was taken at the inlet of the sorting line, the sorting quality was reduced, as expected, due to overlapping of the sorted material and, thus, deterioration of the optical recording under the scanning heads. Compared to Mode A, there was a reduction in sorting clarity quality of 1.16 %.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5 using (9), with the tightness of

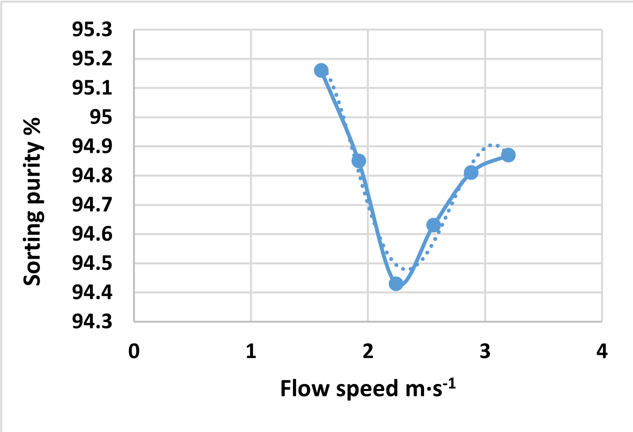

FIGURE 12. Measurement results for regime C.

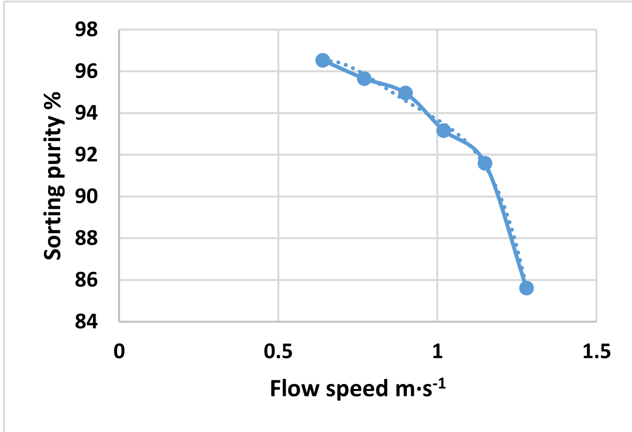

FIGURE 13. Measurement results for regime D.

TABLE 4. Measurement results for regime D.

Flow Speed ($m \cdot s^{-1}$)	Sorting Purity (%)	Difference (%)
0.64	96.53	-3.61
0.77	95.66	-2.74
0.90	94.96	-2.04
1.02	93.17	-0.25
1.15	91.60	1.32
1.28	85.62	7.30
	92.92	

TABLE 5. Measurement results for regime E.

Flow Speed ($m \cdot s^{-1}$)	Sorting Purity (%)	Difference (%)
0.64	96.23	-2.71
0.77	95.27	-1.75
0.90	94.95	-1.43
1.02	94.00	-0.48
1.15	93.27	0.25
1.28	87.42	6.10
	93.52	

agreement between the real and approximated measurement results $R^2 = 0.9682$.

$$\eta_C = 0.8967 \cdot x^5 - 12.293 \cdot x^4 + 65.057 \cdot x^3 - 165.73 \cdot x^2 + 202.58 \cdot x \quad (9)$$

where η_C is the sorting purity coefficient and x is the set conveyor speed.

In conclusion, it can be assumed that repeated automated measurements of Mode C will produce analogous results, i.e. the mean value of the sorting purity coefficient of sorted plastic waste will still oscillate around the 95 % value within an interval of less than 1 %.

D. DAY SHIFT WITHOUT OVERSIZED WASTE COLLECTION AT THE INPUT TO THE LINE/MANUAL MODE

Based on the measurement results (Table 4, Fig. 13), it can be stated that the sorting purity coefficient clearly decreased at the selected conveyor speeds, again with a significant decrease at the highest conveyor speed.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5 expressed with (10), with the tightness of agreement between the real and approximated measurement results $R^2 = 0.9963$.

$$\eta_C = -90.412 \cdot x^5 + 155.63 \cdot x^4 + 167.08 \cdot x^3 - 542.5 \cdot x^2 + 403.89 \cdot x \quad (10)$$

where η_C is the sorting purity coefficient and x is the set conveyor speed.

In the manual measurements of mode D, as a result of increasing the conveyor speed, the value of the sorting purity coefficient gradually decreased by 10.91 %.

E. NIGHT SHIFT WITH OVERSIZED WASTE COLLECTION AT THE INPUT TO THE LINE/MANUAL MODE

Based on the measurement results (Table 5, Fig. 14), it can be stated that the sorting purity coefficient clearly decreased at the selected conveyor speeds, again with a significant decrease at the highest conveyor speed.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5 (11), with the tightness of agreement between the real and approximated measurement results $R^2 = 0.995$.

$$\eta_C = -109.03 \cdot x^5 + 192.12 \cdot x^4 + 167.54 \cdot x^3 - 571.92 \cdot x^2 + 415.62 \cdot x \quad (11)$$

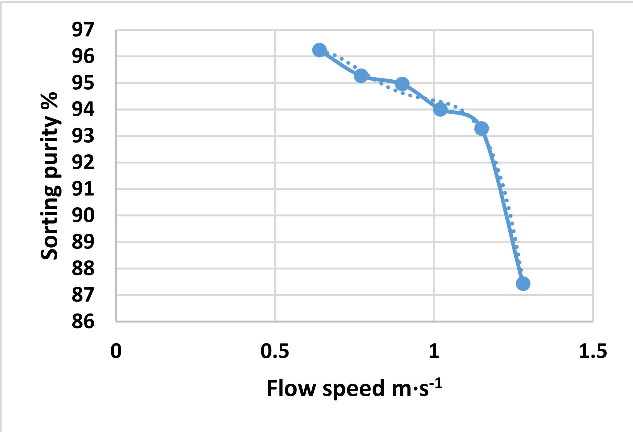

FIGURE 14. Measurement results for regime E.

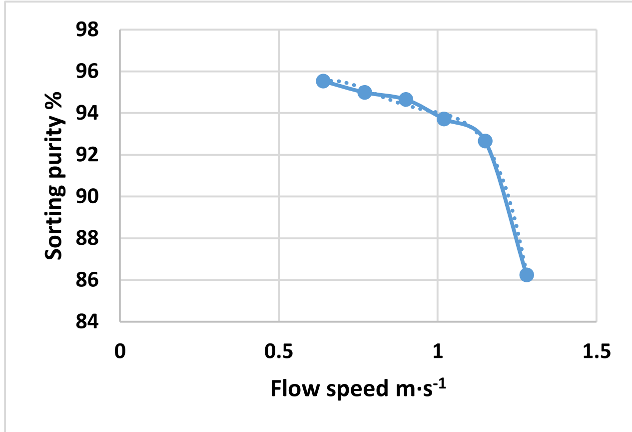

FIGURE 15. Measurement results for regime E.

TABLE 6. Measurement results for regime F.

Flow Speed ($m \cdot s^{-1}$)	Sorting Purity (%)	Difference (%)
0.64	95.53	-2.57
0.77	94.99	-2.03
0.90	94.65	-1.69
1.02	93.71	-0.75
1.15	92.65	0.31
1.28	86.24	6.72
	92.96	

where η_C is the sorting purity coefficient and x is the set conveyor speed.

In the manual measurements of mode E, the value of the sorting purity coefficient was gradually reduced by 8.81 % as the conveyor speed increased.

F. NIGHT SHIFT WITHOUT OVERSIZED WASTE COLLECTION AT THE INPUT TO THE LINE/MANUAL MODE

Based on the measurement results (Table 6, Fig. 15), it can be stated that the sorting purity coefficient clearly decreased at the selected conveyor speeds, again with a significant decrease at the highest conveyor speed.

The trend of the dependence of the sorting purity coefficient on the conveyor speed can be approximated by a polynomial curve of degree 5 (12), with the tightness of agreement between the real and approximated measurement results $R^2 = 0.9972$.

$$\eta_C = -141.19 \cdot x^5 + 323.88 \cdot x^4 - 37.733 \cdot x^3 - 428.83 \cdot x^2 + 377.9 \cdot x \quad (12)$$

where η_C is the sorting purity coefficient and x is the set conveyor speed.

FIGURE 16. (a) Sample of sorted waste, (b) manual removal of contamination.

In the manual measurements of mode F, the value of the sorting purity coefficient gradually decreased by 9.29 % as the conveyor speed increased.

The quality of sorting of plastic waste with a value of the tested coefficient above 95 % is a limit value that is accepted by the market in terms of further processing of the material, so the operator aims to achieve this value or preferably exceed it.

Figure 16(a) shows an illustration of one of the samples of sorted plastic waste, and Fig. 16(b) shows an employee of the sorting line operator manually removing contamination from a sorted sample.

TABLE 7. Comparison of the desired values of the sorting purity coefficient of waste plastic sorting.

	Manual modes						Automated modes					
	0.64 $m \cdot s^{-1}$	0.77 $m \cdot s^{-1}$	0.90 $m \cdot s^{-1}$	1.02 $m \cdot s^{-1}$	1.15 $m \cdot s^{-1}$	1.28 $m \cdot s^{-1}$	1.60 $m \cdot s^{-1}$	1.92 $m \cdot s^{-1}$	2.24 $m \cdot s^{-1}$	2.56 $m \cdot s^{-1}$	2.88 $m \cdot s^{-1}$	3.20 $m \cdot s^{-1}$
A	-	-	-	-	-	-	96.30	95.99	95.54	95.73	95.99	96.15
B	97.21	96.41	96.01	x	x	x	-	-	-	-	-	-
C	-	-	-	-	-	-	95.16	x	x	x	x	x
D	96.53	95.66	x	x	x	x	-	-	-	-	-	-
E	96.23	95.27	x	x	x	x	-	-	-	-	-	-
F	95.53	x	x	x	x	x	-	-	-	-	-	-

TABLE 8. Economic results for automated regime with oversized waste removal.

Processing costs:				**636,191 €**	**Revenues from waste processing:**				**883 309 €**
CAPEX				2,200,000 €	Processing fee	17%	6000	150	459000 €
Dpreciations/Gy.)	6			366,667 €	PET transp sale	370	5%		333000 €
OPEX (2x4workers)	8	1621	12	155,635 €	PET blue sale	50	3%		27000 €
Energies	120	120	6000	86,400 €	PET green sale	60	4%		43200 €
Service:				8,000 €	PET coloured mix sale	30	5%		27000 €
Investment interest (100%)	1,5%			19,489 €	Sorting purity	96,15%			0 €
					Unsorted waste fee	3,85%		50	-5891 €
EBITDA:				633,274 €					
EBT:				247,118 €					
NPV after 6y.				1,599,642 €					

TABLE 9. Economic results for manual mode with oversized waste collection in the day shift.

Processing costs:				**368 643 €**	**Revenues from waste processing:**				**242228 €**
CAPEX				250 000 €	Processing fee	17%	6000	150	128 520 €
Dpreciations/Gy.)	6			41 667 €	PET transp sale	350	5%		88 200 €
OPEX (2x7 workers)	14	1621	12	272 362 €	PET blue sale	50	3%		7560 €
Energies	70	120	6000	50 400 €	PET green sale	60	4%		12096 €
Service:				2000 €	PET coloured mix sale	30	5%		7560 €
Investment interest (100%)	1,5%			2 215 €	Sorting purity	96,01%			0 €
					Unsorted waste fee	3,99%		50	-1708 €
EBITDA:				-82534 €					
EBT				-126 415 €					
NPV after 6y				-745 203 €					

It can be clearly stated that the most efficient mode is mode A, i.e. the automated mode with oversized waste collection. Automated mode C without oversized waste collection is only effective at the lowest conveyor speed.

Manual modes B, D, E, and F are not effective over the full range of conveyor speed settings. Mode B appears to be the most effective for the three lowest conveyor speeds, where the effect of oversized waste removal is evident. D day mode with no collection and E night mode with oversized waste collection can be considered relatively comparably effective. Mode F, with the worst operating conditions, i.e. manual, night-time and no collection of oversized material, is the least efficient mode for the treatment of waste plastic by sorting.

TABLE 10. Economic results for a manual mode without oversized waste collection in the day shift.

Processing costs:				**288 211 €**	**Revenues from waste processing:**				**172911 €**
CAPEX				300000 €	Processing fee	17%	6000	150	91800 €
Dpreciations /6y.)	6			50 000 €	PET transp sale	350	5%		63000 €
OPEX (2x7 workers)	12	1621	12	233 453 €	PET blue sale	50	3%		5400 €
Energies	70	120	12	101 €	PET green sale	60	4%		8640 €
Service:				2 000 €	PET coloured mix sale	30	5%		5400 €
Investment interest (100%)	1.5%			2 658 €	Sorting purity	95,66%			0 €
					Unsorted waste fee	4,34%		50	-1329 €
EBITDA:				-62 643 €					
EBT:				-115301€					
NPV after 6y				-675 858 €					

V. ECONOMIC EVALUATION OF THE SORTING PROCESS

Based on the measurements and analysis of the results of the measurements of the different variants of the treatment process, it can be shown that manual sorting of waste is not only insufficiently efficient in terms of the purity of waste material sorting but is also economically unsatisfactory. From an economic and process point of view, the set-up at 100 % flow rate (highest conveyor speed) of the waste material is the most advantageous because the sorting line produces (sorts) up to twice as much waste as at half speed.

The return on investment as one of the commonly considered and desired economic parameters cannot be clearly determined because the amount of investment in both processing modes (automatic/manual) differs significantly. Mode C can be considered fully automated, while the most efficient mode A is, in principle, partially automated because it is combined with manual pre-sorting of oversized waste. Therefore, the net present value (NPV) was calculated as a financial variable expressing the total present value of all cash flows related to the profitability of the investment project due to the consideration of the time factor. In addition, the annual operating profit excluding finance costs (EBITDA = earnings before interest, taxes, depreciation and amortisation) was calculated together with the profit before tax, which also takes into account the amount of interest and depreciation. The discount rate applied was 2.5 % and was directly related to the investment and its depreciation over six years within the depreciation group of the sorting line.

A. AUTOMATED SORTING MODE WITH OVERSIZED WASTE COLLECTION AT THE INPUT

From a financial point of view, the automated mode involves a higher investment intensity but, at the same time, lower operating costs (OPEX) associated with a minimum number of employees. Table 8 declares the economic indicators achieved under the scheme.

It is clear from this table that the line is able to generate a positive operating result during the period under evaluation due to the higher plastic processing capacity. According to the result, the payback period of the investment is up to 6 years.

B. MANUAL SORTING MODE WITH OVERSIZED WASTE COLLECTION AT THE INPUT, DAY SHIFT

Manual operation in daily operations means lower investment costs but, on the other hand, a higher operational burden due to increased labour costs per employee. Table 9 illustrates the operation of the sorting line in this setting.

C. MANUAL SORTING MODE WITHOUT COLLECTION OF OVERSIZED WASTE AT THE INPUT, DAY SHIFT

The investment and operational setup is similar to the manual sorting mode with the collection of oversized waste at the input during the day shift, and the difference is only in the reduction of the number of employees (2 employees are not needed to sort oversized waste at the input). On the other hand, the sorting results were not as good as in the case of pre-sorting (Table 10).

In conclusion, the automated sorting option implemented at the highest speed (3.2 $m \cdot s^{-1}$) will achieve the highest market return on investment within six years and, at the same time, with efficient sorting of waste material (achieving purity of plastic waste above 95 %), can represent, in addition to capital expenditure, ongoing capital income, i.e. the annual income that a one-off investment will generate over its lifetime. However, due to low capacity limits, manual schemes are not able to cover the necessary volumes of waste treated to cover the investment and operating costs associated with the operation of the line over the investigated period.

From the point of view of the economic evaluation, the return and evaluation of the investment in the specified period of six years have been demonstrated only for the automated mode, especially in terms of the quality of sorting and processing capacity, which is in technical practice incomparably higher than in the manual mode (the need to cover the wages for workers for the arduous and monotonous work on the conveyor belt is eliminated).

VI. CONCLUSION

Current and forthcoming legislation in the field of waste management obliges waste handlers to sort waste as efficiently as possible and thus reduce the volume of landfilling. In particular, the management of plastic waste has been and will continue to be monitored because PET material is not only a valuable material contained in municipal waste, but its natural decay in nature takes decades to 100 years, and the level of pollution is dangerous for nature and the human organism in the long term. Therefore, according to the EU Directive (2019/904), from 2025, EU Member States will have a binding target that all PET beverage bottles must contain at least 25 % recycled plastic and by 2030, all plastic bottles must contain at least 30 % recycled material. The technological (mechanical) treatment of waste through automated and efficient sorting and preparation for further processing is the first step towards its total recycling in the context of the circular economy in society.

Currently, the most widely used automated sorting systems include optical systems that work on the principle of electromagnetic wave generation in visible radiation, reception and evaluation. On a selected sorting line equipped with such optical systems, measurements were carried out to analyse the achievement of the main sorting parameter – the purity of sorting of plastic waste at a given processing capacity (at set speeds of sorting conveyors/waste material flow).

The measurements were carried out on a sorting line equipped with an optical detection system of NIR/VIS machines Autosort from Tomra Sorting Solutions, i.e. in an automated sorting system consisting of optical systems and a manual sorting cabin with a bypass system connected to the input part of the line (in case of failure on the optical part). In the presented case, the measurement was used as a separate sorting part to eliminate the effect of optical sorting.

The operating modes set were day and night shift (in order to assess the effect of daylight or mental fatigue), sorting method with and without removal of oversized material at the input of the sorting line, automated and manual mode. The conveyor belt speed for manual sorting was set between 0.64 and 1.28 $m \cdot s^{-1}$, for automated sorting between 1.6 and 3.2 $m \cdot s^{-1}$.

Results with a desired sorting purity of plastic waste above 95 % were achieved at all conveyor speed settings only in the automated mode with pre-sorting of oversized materials at the input of the line, while without pre-sorting only at the lowest speed (1.6 $m \cdot s^{-1}$).

In manual modes, the desired sorting quality results were only achieved at the lowest conveyor speeds, which significantly reduces production because twice as much waste material is sorted at the maximum conveyor speed than at half the speed.

It can be concluded that in terms of the production process, the automated sorting mode is an order of magnitude more efficient than the manual mode, resulting in much more significant economic results. For example, more than 95 % of the waste material flows through the sorting line as a result of the high-quality sorting of plastic waste. In the case presented here, the capacity is 2.85 $t \cdot h^{-1}$.

As manual sorting systems are still widely used and the amount of investment in automated sorting systems is still debated, the operational and economic justification for the installation of automated optical sorting systems has been demonstrated based on the measurements made and the interpretation of the results of these measurements, with regard to the return on investment (six years) and in the context of the processing capacity and the achieved purity values for sorting plastic waste.

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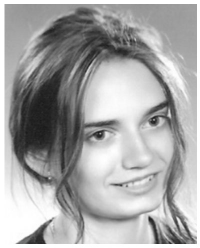

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