A Fuzzy Multi-Criteria Model for Municipal Waste Treatment Systems Evaluation including Energy Recovery

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Abstract: One of the recent problems on waste sorting systems is their performance evaluation for proper decision making and management. For this purpose, multi-criteria methods can be used to evaluate the sorting system from both operational and financial perspectives. According to a recent literature review, there are no solutions for evaluating waste sorting systems that take into account: sorting point utilisation, sorting efficiency, waste stream irregularity, and technical system availability. In addition, the problem of data uncertainty and the need to use expert judgements indicate the need for the implementation of methods adjusted to the qualitative and quantitative assessment, such as the fuzzy approach. Following this, in order to overcome the presented limitations, the authors introduced the new assessment method for waste sorting systems based on multi-criteria model implementation and fuzzy theory use. Therefore, the developed model was based on a hierarchical fuzzy logic model for which appropriate membership function parameters and inference rules were defined. The specificity of the chosen assessment criteria and their justification was provided. The model has been implemented to evaluate one of the waste sorting plants in Wroclaw, Poland. Tests have been conducted for seven different configurations of waste sorting lines (with variable input parameters). The study focuses on analysing the amount of selected waste at each station in relation to the total stream size of each fraction. Efficiency was measured by the mass of the collected waste and the number of pieces of waste in each fraction. Based on the obtained results, estimations of particular parameters of the model were made, and the results were presented and commented on. It was shown that there is a significant relationship between the level of system evaluation and sorting efficiency and an inverse relationship with the level of RDF obtained. The analysis was based on Pearson’s linear correlation coefficient estimation and linear regression implementation.

Keywords: waste management; waste sorting; sorting line; system evaluation; multi-criteria evaluation

1. Introduction

Socio-economic development determines an increase in the intensity of material consumption on a global scale. This increase occurs despite the orientation of the economy towards the rationalisation of production, services, and technologies. In order to minimise the amount of waste sent to landfills and incineration, due to the rapid depletion of landfill space and emissions of air pollutants from incineration, recycling is preferred [1] and, at a lower level of the waste treatment hierarchy, recovery (for example, by burning alternative fuel (RDF)). In 2018, the production of municipal solid waste (MSW) in 28 countries of the European Union reached 250.6 Mt, with the adoption of different management strategies involving recycling (48 wt%), incineration and thermal valorisation (29 wt%), and landfilling (23 wt%) [2].

A report issued by the European Commission in 2018 identified as many as 18 countries (out of 28) at risk of not achieving the required 50% recycling rate in 2020 [3]. One of the problems presented as an obstacle to achieving the required recovery levels is the lack of modern solutions in the available infrastructure. Therefore, to achieve the required level, it
is necessary to develop innovative solutions and technologies to increase the effectiveness of the waste sorting process and improve the current management.

An effective measure to reduce the amount of waste generated is to switch from the traditional linear to the circular economy model [4,5]. Despite the increase in interest and activities in this area, it is estimated that only about 8.6% of the global economy in 2019 was circular [3]. The remaining amount is subordinated to the traditional model, in which end-of-life objects become part of reverse logistics.

1.1. Literature Review

The traditional waste management system consists of four subsystems: waste generation system, waste collection system, waste treatment system, and waste storage and disposal system [6].

The elements of the waste treatment subsystem, such as waste-to-energy facilities, material recovery facilities (MRF), and mechanical-biological treatments (MBT), are of the greatest importance in the possibility of using waste for energy generation. Many works focus on the so-called waste-to-energy facilities [7–9]. However, the energy aspect is neglected in material recovery facilities and mechanical-biological treatments, which are significant sources of material used as an alternative fuel.

MRFs and MBTs are part of the waste treatment system subsystem. Municipalities use them to treat mixed MSW to increase resource recovery as a supplement or replacement to source selection [10]. One of the distinguishing factors of these systems is the high irregularity of the input stream [11–13]. The sorting process involves a sequence of unit operations that include air classification, ballistic separation, eddy current separation, magnetic separation, screening, and size reduction [14].

There are two main types of MBT technology: mechanical-biological pre-treatment (MBP) and mechanical-biological stabilisation (MBS) or bio-drying. In MBP, the organic fraction is separated and biologically stabilised before landfilling, and recyclables are recovered from the remaining coarse fraction and RDF. In MBS, waste is first composted to dry before extracting the larger RDF fraction [15,16]. The processing method significantly impacts the quality of the resulting RDF and, consequently, their energy value, which is influenced by the calorific value, moisture content, non-flammable component content and content of various substances (including heavy metals and gases).

MRF and MBT are evaluated for different groups of factors: economic, technical, and ecological [17]. The analysis of the MRF and MBT assessment methods adopted in the literature is presented in Table 1 with a summary of the used indicators.

| Recycling Indicator | CO₂ Emission | Recovery | Grade | Efficiency | Workability | Productivity Indicator | Yield Indicator | Purity Indicator | Compliance Indicator | Economic | Operation Experience |
|---------------------|--------------|----------|-------|------------|-------------|------------------------|----------------|-----------------|----------------------|----------|----------------------|
| [18]                | +            | +        |       | +          |             |                        |                 |                 |                      |          |                      |
| [17]                |              | +        | +     | +          | +           | +                     |                 |                 |                      |          | +                    |
| [19]                | +            | +        |       |            |             |                        |                 |                 |                      |          |                      |
| [12]                | +            | +        |       | +          | +           |                        |                 |                 |                      |          |                      |
| [20]                |              |          |       |            |             |                        |                 | +               |                      |          | +                    |
| [21]                |              | +¹       |       |            |             |                        |                 |                 |                      |          |                      |
In Reference [20], the authors undertook to apply a new comprehensive approach to the long-term techno-economic evaluation of the performance of sorting plants for plastic waste recovery. The authors point out that MRF performance evaluation is carried out using different approaches even with respect to the time frame, which makes it difficult to compare the results.

In Reference [18], the authors presented a case study from Spain that analysed the characteristics of input streams and final products from two types of recycling plants. The analysis aimed to determine the maximum efficiency of sorting systems for building demolition waste. The methodology presented by the authors allows a preliminary classification of options for the management of products resulting from sorting.

Bottom ash from municipal solid waste incineration is usually processed to recover valuable raw materials, such as metals, and to produce mineral material for use in construction or destined for disposal. In Reference [21], the author presented a model to evaluate the quality and quantity of materials obtained using different recovery methods. The authors in Reference [22] presented a life-cycle assessment (LCA) of a bottom ash management and recovery system to identify environmental tipping points beyond which the burdens of recovery processes outweigh the environmental benefits of metal and mineral aggregate valorisation. In the next work, Reference [28], the authors assessed the technical possibilities of recovering the mineral fraction contained in compost (CLO) on a processing line designed for glass recovery. Such action fits into the EU strategy focused on circular waste management.

A different approach was presented in Reference [24], where the authors proposed a comparison of available techniques used to treat electronic waste (e-waste) at an MRF in the state of California. The analysis was concerned with comparing the economic aspects of using the different techniques.

In Reference [25], the authors analysed the recovery of beverage cartons at three light packaging waste treatment plants at different input materials and input weights. The authors highlighted uncertainties in how waste samples were collected to determine the various indicators. The article aimed to indicate the good practices necessary for proper waste sampling. In a subsequent publication, the same authors, in Reference [26], presented a methodical approach to the evaluation of waste treatment results. The basis was the analyses presented in the previous publication, while the result of the publication was the presentation of a method based on a decision tree.

| Indicator                      | CO₂ Emission | Recovery | Grade | Efficiency | Workability | Productivity Indicator | Yield Indicator | Purity Indicator | Compliance Indicator | Economic | Operation Experience |
|-------------------------------|--------------|----------|-------|------------|-------------|------------------------|----------------|-------------------|----------------------|----------|----------------------|
| [22]                           |              |          |       |            |             | 1 +                    |                |                   |                      |          |                      |
| [23]                           |              |          |       |            |             | +                     |                |                   |                      |          |                      |
| [24]                           |              |          |       |            |             | +                     |                |                   |                      |          |                      |
| [6]                            | + 1          |          |       |            |             | +                     |                |                   |                      |          |                      |
| [25]                           |              |          |       |            |             | +                     | +              |                   |                      |          |                      |
| [26]                           |              |          |       |            |             | +                     | +              |                   |                      |          |                      |
| [27]                           |              |          |       |            |             | +                     |                |                   |                      |          |                      |
| Total                          | 1            | 1        | 12    | 2          | 1           | 1                     | 3              | 6                 | 1                    | 4        | 1                    |

1 In terms of the recovery of individual elements.
Due to the increasing demands on waste sorting systems, they are becoming more complex to provide greater material recovery from products with complex material mixtures. In order to increase efficiency and process complex material mixtures, separation systems are usually organised as highly integrated multi-stage systems. Therefore, in Reference [19], the authors have proposed an approach for modelling, analysing, and designing multi-stage separation systems to meet specific recovery/classification performance objectives. A similar approach can be found in Reference [12], where the authors presented a tool for predicting the performance of sorting systems and showed how performance depends on the system configuration and parameters, as well as the input materials.

An interesting approach was presented in Reference [29], where the authors presented a probabilistic model of material separation processes. The model is generic and can be used to analyse the performance of recycle processes and material recycling systems, as well as other separation and purification processes.

In Reference [27], the authors evaluated the limitations of using published partition coefficient datasets to model the sorting performance of mechanical unit operations commonly found in material recovery facilities (MRFs). A partition coefficient is generally defined as a ratio between 0 and 1 corresponding to the fraction of an input stream that ends up in a specific output stream. In Reference [23], the authors presented the results of research work, which consisted of checking and evaluating the automation of municipal waste sorting plants by supplementing or replacing manual sorting by sorting by a robot with artificial intelligence.

The articles presented so far indicate different approaches to the evaluation of sorting systems. Their basis is based on a set of indicators, but the final assessment is based only on the comparison of individual indicators among themselves or reference to specific standards. In the literature, many publications approach the problem of evaluation in a more comprehensive way. This is evidenced by the following literature reviews, References [30,31] that analyse the use of multi-criteria methods (MCDM). In Reference [30], the authors performed a state-of-the-art analysis based on 260 articles. They analysed the combinations of the criteria used in the articles, mainly social, economic, and environmental. Only 2% of the methods dealt with recycling centres/sorting plants/MRF, but they did not consider the operational criteria. The second review cited, Reference [31], has shown that recycling is the most-researched problem in the literature. That is, 27 studies out of 80 have investigated the recycling problem. Most of these studies are about finding the best recycling technology/strategy. The vast majority of the articles dealing with the issue of sorting systems evaluation use the life cycle assessment method (LCA) (see, for example, References [13,16,32]) or life cycle cost (LCC) (see, for example, Reference [33]).

In Reference [17], the authors evaluated the performance of a large material recovery facility based on a selected set of parameters. The chosen parameters were used to create a dashboard to help managers make system management decisions.

In Reference [6], the authors have presented an integrated assessment of production processes in ecological, technical, and economic terms. The presented method was analysed in relation to the recovery of materials during iron and steel production. The method aimed to support investors’ decisions in order to receive the best ecological results. This may not be a very popular approach, but the authors have shown that methods based on multi-criteria methods (MCDM) can also be effectively used for decision-making in the area of environmental impact as methods based on life cycle analysis (LCA). The current evaluation approaches do not analyse the issue of RDF production as a component for evaluation.

1.2. The Research Aim

In summary, the development of waste sorting systems management solutions caused the need to create tools that (a) will allow for assessing of the current efficiency level, (b) indicate the directions of further development/changes that provide the possibility to achieve environmental and law requirements, and (c) include assessment approaches taking into account the operational and financial perspectives. In addition, waste sorting
systems performance evaluation, on the one hand, is particularly challenging and requires taking into account specific aspects of waste type and waste treatment possibilities. On the other hand, the problem with data uncertainty and quality needs to be investigated.

For this reason, the authors focus on the specificity of multi-criteria assessment methods implementation for waste sorting semi-automatic systems effectiveness evaluation. The introduced evaluation methods consider different parameters of a system evaluation (e.g., sorting point efficiency, sorting line efficiency index, an uneven load of stations, availability of waste sorting lines). The proposed approach is also based on fuzzy theory use in order to assess the evaluation index \( EI \) for the waste sorting system performance.

Following this, the main contribution of this study is that:

- We have defined the assessment parameters for waste sorting system efficiency, which are essential for waste sorting processes performance.
- We have introduced a two-step assessment method to assess the waste sorting system efficiency based on fuzzy theory use.
- We have implemented the proposed method to verify its diagnostic function and determine its labour intensity.
- We have analysed the impact of the system evaluation on RDF energy quality and sorting efficiency.

The present paper aims to develop a multi-criteria evaluation method that considers the different parameters of a system evaluation (e.g., sorting point efficiency, sorting line efficiency index, an uneven load of stations, availability of waste sorting lines).

The article consists of the following parts as follows. Section 1 indicates a research gap that will be filled by the model presented in Section 2. Sections 3 and 4 present the model using a selected real system as an example and discuss the results obtained. Section 5 presents the conclusion of the paper.

2. A Fuzzy Multi-Criteria Model for Evaluating Municipal Waste Treatment Systems

The described method consists of a fuzzy model of the treatment system and an analysis of the impact of system evaluation on RDF energy quality and sorting efficiency. To consider the aspect of the treatment system’s energy potential, the assessments obtained from the model should be compared with the RDF energy quality and efficiency (analysis presented in Chapter 3).

In the presented method, a two-stage assessment is used in which the collection points are assessed first and then the system. However, due to the nature of the input and output data, the method can be used to assess both the system and any part of it (line, set of automatic sorting machines, etc.).

The method described was developed as part of a research project in accordance with the methodology described in References [30,34]. Twenty-three employees (including sorting plant managers and 18 system employees) were selected for the preparation.

Surveys were conducted on a quarterly basis to determine the criteria and values of the variables for each membership function. The periodicity of the survey was intended to eliminate intuitive responses based on current system parameters. Based on the results obtained, an analysis was carried out to calculate the values to be assessed. Due to the high uncertainty of the data, a method based on fuzzy logic was chosen (it is recommended in case of uncertainty in the input data). The next step was to define the names of membership function and to transfer the survey results into linguistic variables. Based on the results, we ran a regression to determine the shape of the membership function. The result indicated that triangular functions could be used. The values of the individual variables were then determined based on expert opinion. For example, this gives unambiguous results in contrast to Gaussian functions.

Figure 1 shows a hierarchical fuzzy logic model for evaluating municipal waste treatment systems. The output variable of the model is the waste treatment system evaluation index \( EI \). It depends on the values of four input variables:
The waste stream irregularity \((WV)\) is calculated for a variable amount of waste processed in a specific time unit. The selected time unit must be identical to the one for which the workstation productivity was determined. The flux non-uniformity informs about the influence of flux variability (deviation from the average) on the workstation performance. The membership functions of the waste stream irregularity are presented in Figure 3.

Figure 3. The membership functions of the waste stream irregularity.

The utilisation rate of sorting points \((PU)\) is determined from the average value of the utilisation rate of all sorting points in the waste treatment system. The utilisation rate of individual points is determined based on a fuzzy model, where the inputs are the point efficiency rate \((WP)\) and the waste stream irregularity \((WV)\) for the evaluated point. The waste sorting points are mechanical devices used for waste sorting and manual sorting stations.

Sorting point efficiency \((WP)\) is expressed as a ratio of the total amount of sorted waste on the tested sorting station to the assumed productivity. It results from the technical parameters of a device or the predispositions of a workstation. The form of the membership function of the sorting point efficiency variable is shown in Figure 2. Index \(k\) corresponds to the sort line number, and \(j\) is the number of the workstation being evaluated.

Figure 2. The membership function of the linguistic variable of the sorting point efficiency.

The utilisation rate of sorting points \((PU)\).
- Treatment System Performance Indicator \((PE)\).
- Indicator of irregularity of workstation stream in the waste treatment system \((WVT)\).
- Waste Treatment System availability Indicator \((A)\).

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Figure 3. The membership function of the linguistic variable of the irregularity waste stream.

Determination of the inference rules and membership functions was made on the basis of experts’ opinions. The experts were employees (management staff) of waste treatment facilities. They established a four-grade scale for the evaluation of points, together with the factors influencing the process, and determine the weights for the indicators. The presented membership functions and inference rules are the interpretation of the obtained opinions.

The average value of the obtained sharpened values of the sorting point utilisation index is the input variable for the fuzzy waste treatment system evaluation model. The membership function of the linguistic variable of the sorting point utilisation rate is presented in Figure 4.

Figure 4. The membership function of the linguistic variable of the sorting point utilisation rate.

The effectiveness of a treatment system (PE) is defined as the ratio of correctly sorted waste fractions to the total amount of waste that has been sorted.

\[
P_E = \frac{\sum_{j=1}^{\bar{S}_1} \sum_{l=1}^{n} O_j^l - \sum_{k=2}^{n} S_j^k}{S_1}, \quad \text{for } j = 1, \ldots, n; \ k = 1, \ldots, n, \tag{1}
\]

where: \(O_j^l\) — total weight of sorted waste streams at the \(j\)-th evaluated workstation in \(k\)-th line, \(S_j^l\) — total weight of the waste stream at the \(j\)-th evaluated workstation on \(k\)-th line, and \(S_1\) — total weight of the waste stream input.

The membership function of the linguistic variable in the effectiveness of the processing system (PE) is presented in Figure 5.

Figure 5. The membership function of the linguistic variable in the effectiveness of the processing system.
The value of $a_{PE}$ is assumed to depend on the values of the minimum recovery levels set out in the regulation of the authorities of the country concerned. Results that are less than the indicated value are considered unacceptable.

The irregularity of the workstation load is determined by the unevenness coefficient calculated from the formula:

$$WV_{TP} = \frac{\sum_{i=1}^{N} (WP_j^k - \overline{WP}_j^k)^2}{N},$$

where: $WP_j^k$—unevenness coefficient of sorted waste streams at the $j$-th evaluated workstation in $k$-th line, $\overline{WP}_j^k$—mean value of the unevenness coefficient calculated for the $j$-th evaluated workstation on $k$-th line, and $N$—number of observations. $WV_{TP} \in [0, 1]$.

This indicator makes it possible to determine the correctness of the processing system due to the workstation load. The membership function of the linguistic variable irregularity of workstation load is presented in Figure 6.

![Figure 6](image)

**Figure 6.** The membership function of the linguistic variable irregularity of workstation load.

Waste treatment systems, due to the nature of their work, are exposed to frequent breakdowns and downtimes. It results in a significant proportion of the average time spent in a failed state. In addition, each downtime of a treatment system is repeatedly associated with a lengthy restoration of the system to full load operation. Below the minimum readiness $a_A$, the system operating at the current load (the size of the input stream) is not able to process all the input material. The membership function of the linguistic variable availability of the processing system is presented in Figure 7.

![Figure 7](image)

**Figure 7.** The membership function of the linguistic variable availability of the processing system.

Since only those systems are capable of processing the total stream of collected waste sorting, efficiency becomes a key criterion. It implies the requirement to achieve minimum recovery rates and, at the same time, has a real impact on the company’s revenue. The rules have been developed on this basis, which state that, if the system fails to achieve the minimum recovery level, the assessment value is unacceptable. Otherwise, the importance of the availability and utilisation indicator increases. The fourth indicator is used when the utilisation level of a treatment system informs about the available unused processing
capacity. It is used to assess the correctness of the waste stream selection along with its unevenness. Based on the research conducted, 49 inference rules were developed (found in the appendix).

The membership function of the output variable evaluation of the waste treatment system is presented in Figure 8.

![Membership function](image)

**Figure 8.** The membership function of the output variable evaluation of the waste treatment system.

After performing the inference using the described membership functions and rules, the result is obtained in the form of fuzzy sets. The quantification of the fuzzy values to the real value is carried out using the centre of gravity method. MATLAB R2017a software was used for this.

### 3. Model Application—Case Study

In order to evaluate the waste processing system using the method described in this paper, tests were conducted in one of the sorting plants in Wroclaw (Poland) for selectively collected waste (metal and plastic). The system under study was dedicated only to sorting selectively collected waste. The system studied consisted of three lines for sorting fractions of different sizes. In addition, on individual lines, there are other devices, such as induction sorters, gravity sorters, magnetic sorters, etc. Due to the complexity of the system, the paper presents the application of the method only for a selected fragment of the system. However, the method was verified on the basis of the full system and was accepted by experts. Only a part of the sorting installation dealing with sorting of a waste stream with a fraction between 50 mm and 170 mm has been included in the evaluation. Figure 9 presents a drawing with the designation of individual sorting stations.

![Sorting line](image)

**Figure 9.** Scheme of the sorting line.

At each workstation, workers face each other and select the same types of waste. Table 2 presents the type of waste sorted at each workstation. Between the workers, there are chutes into which they throw sorted waste. In the case of workstations 2 to 5, apart from chutes, the workers have bags into which they throw fractions other than those thrown into the chutes.
Table 2. Types of waste sorting on individual workstations.

| Workstations | Picking Fractions                          |
|--------------|--------------------------------------------|
| 1            | Blue PET                                   |
| 2            | Blue PET, White PET, Aluminium, Tetra Pak  |
| 3            | Blue PET, White PET, Aluminium, Tetra Pak  |
| 4            | Blue PET, Green PET, White PET, Aluminium, Tetra Pak |
| 5            | Blue PET, Green PET, White PET, Aluminium, Tetra Pak, HDPE |

The study included an analysis of the amount of selected waste at each station in relation to the total stream size of each fraction. Efficiency was measured by both the mass of collected waste and the number of pieces of waste in each fraction. In the present paper, the mass ratio was used to determine efficiency.

Based on the findings of the experts, the values of the individual linguistic variables were determined. They are presented in Table 3.

Table 3. Values of individual linguistic variables.

| Designation of Assessment Indicator | Symbol for a Linguistic Variable | Values of the Linguistic Variable |
|------------------------------------|----------------------------------|----------------------------------|
| $WP_j$                             | $a_{WP_j}$                       | 0                                |
|                                    | $b_{WP_j}$                       | 0.5                              |
|                                    | $c_{WP_j}$                       | 1                                |
| $WV_j$                             | $a_{WV_j}$                       | 0                                |
|                                    | $b_{WV_j}$                       | 0.56                             |
| $PU$                               | $a_{PU}$                         | 0                                |
|                                    | $b_{PU}$                         | 0.333                            |
|                                    | $c_{PU}$                         | 0.666                            |
|                                    | $d_{PU}$                         | 1                                |
| $PE$                               | $a_{PE}$                         | 0.16                             |
|                                    | $b_{PE}$                         | 0.37                             |
|                                    | $c_{PE}$                         | 0.58                             |
|                                    | $d_{PE}$                         | 0.79                             |
|                                    | $e_{PE}$                         | 1                                |
| $WV_{tp}$                          | -                                | -                                |
| $A$                                | $a_A$                            | 0.89                             |
|                                    | $a_A$                            | 1                                |

The study was conducted in 7 independent experiments and included one shift of plant operation (4 h) at a time. The data were collected to estimate the input parameters of the proposed waste treatment system evaluation model. Table 4 presents the evaluation parameters of the sorting points for seven cases.
Table 4. Values of WP$_j$ and WV$_j$ indicators for particular workstations.

| Case 1 | WP1 | WP2 | WP3 | WP4 | WP5 | WV1 | WV2 | WV3 | WV4 | WV5 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.222  | 0.202 | 0.428 | 0.391 | 0.394 | 0.690 | 1.185 | 0.500 | 0.710 | 0.754 |
| Case 2 | 0.168 | 0.182 | 0.413 | 0.236 | 0.302 | 0.754 | 0.964 | 0.441 | 0.615 | 0.700 |
| Case 3 | 0.195 | 0.198 | 0.490 | 0.248 | 0.377 | 0.648 | 0.982 | 0.361 | 0.553 | 0.621 |
| Case 4 | 0.216 | 0.249 | 0.319 | 0.268 | 0.332 | 0.682 | 0.980 | 0.481 | 0.589 | 0.645 |
| Case 5 | 0.208 | 0.258 | 0.408 | 0.284 | 0.314 | 0.656 | 0.935 | 0.446 | 0.604 | 0.747 |
| Case 6 | 0.203 | 0.280 | 0.404 | 0.235 | 0.482 | 0.598 | 0.793 | 0.374 | 0.574 | 0.621 |
| Case 7 | 0.327 | 0.349 | 0.425 | 0.322 | 0.367 | 0.574 | 0.865 | 0.527 | 0.567 | 0.706 |

According to the assumptions of the method, the data in Table 5 were used to calculate the value of the PU index. This result, along with the other values of the input indicators, are presented in Table 5.

Table 5. Types of waste sorting on individual workstations.

| Case | PU  | PE   | WV$_{TP}$ | A   | EI  |
|------|-----|------|-----------|-----|-----|
| 1    | 0.650 | 0.985 | 0.483 | 1.000 | 6.28 |
| 2    | 0.637 | 0.982 | 0.533 | 1.000 | 6.22 |
| 3    | 0.595 | 0.979 | 0.561 | 1.000 | 6.09 |
| 4    | 0.632 | 0.964 | 0.499 | 1.000 | 6.08 |
| 5    | 0.621 | 0.971 | 0.460 | 1.000 | 6.03 |
| 6    | 0.537 | 0.974 | 0.483 | 1.000 | 5.89 |
| 7    | 0.553 | 0.963 | 0.408 | 1.000 | 5.77 |

The PU index values are relatively low. This is due to the fact that the average waste stream size for individual cases was approximately 575.63 kg/h. In contrast, the installation should process approximately 1000 kg/h at a given station. This relationship can also be seen in the PE value for efficiency. The PE value is very high, but this is due to the low intensity of the work. It is also indicated by the WV$_{TP}$ showing that the workplaces were loaded unevenly. The data obtained during the study show that workstations 1, 2, and 5 were mainly loaded. In the extreme case, on workstation 1, the workers reached an efficiency of 85 pieces per minute on average, while, on workstation 4, approximately 34 pieces of waste per minute was achieved.

There were no system downtimes while conducting the study. This was due to the relatively short research time from the beginning of the shift to the first break for employees (after about four hours).

4. Discussion

The model described hereinafter is generic and can be used to evaluate systems that sort any type of waste. However, from the point of view of systems dealing with sorting selectively collected waste, there is an important relationship between the evaluation values and the energy quality of RDF. Tetra Pak was treated as an average value for the energy content of paper, plastic, and metal.

The following calorific values are presented in Table 6 [35–37].
Table 6. Values of the individual linguistic variables.

| Fraction     | Energy Value [kJ/kg] |
|--------------|----------------------|
| Contaminants | 9000                 |
| PET          | 20,500               |
| HDPE         | 40,092.12            |
| PVC          | 17,408.42            |
| Paper        | 16,747.28            |
| Metal        | 697.8                |

A case study is presented to demonstrate the use of the proposed method. The narrow range of EI results from performing the assessment on a selected portion of the system in several scenarios. When evaluating the whole system, a wider EI scope will be achieved. However, it is impossible to present the entire system as a case study due to its complexity and limited article length. We have presented the possibility of investigating the dependence of energy value on the system’s rating. When applying the method to another sorting system, one should follow the steps of our method and, finally, determine the energy dependence on the value of the grades obtained.

The purpose of a sorting plant is to separate economically significant recyclable materials from other materials. From this point of view, there should be a high correlation between the assessment value and the sorting efficiency of the system. This relationship is presented in Figure 10. The Pearson’s linear correlation coefficient is $R_{xy} = 0.756$ for the rating and the percentage efficiency of waste sorting. The correlation at the presented level may seem low, but the obtained result seems reasonable from the decision-makers’ point of view. It should be noted that, on all workstations from 1 to 5, workers choose the blue PET fraction. It implies a significant difference between the purchase price of a ton of blue PET and the other fractions. From an economic point of view, there is a much higher concentration on selecting higher value materials. Therefore, HDPE is selected only at one last station. As a consequence, the efficiency of picking blue PET is higher than HDPE, for example.

![Figure 10. Regression curve describing the effect of the rating on RDF energy quality.](image-url)

To sum up the above considerations, the method described hereinabove can be used to evaluate systems differing in the scale of the amount of waste processed and dealing with sorting of different materials. Moreover, the method indicates a significant inverse relationship between the obtained evaluation value and RDF quality. Therefore, it may be applied for multi-criteria process optimisation purposes, e.g., when changing the arrangement of workstations and changing priorities in the context of selected fractions at individual workstations.

Regression analysis allows establishing the relationship between quantities while determining the confidence interval for simple linear regression. It allows estimating deviations from the nominal level of the relationship between the quantities of the system evaluation level and the RDF calorific value. The estimation of confidence intervals for the parameters of the simple linear regression was developed using Reference [38]. An alpha significance level of 0.05 was assumed. Based on the confidence interval, the expert can read off the range of RDF energy depending on the focus on a particular type of fraction (most often, as a result of differences in the cost of selling raw materials, PET recovery is preferred).
As mentioned before, there is also a relationship between the evaluation value obtained from the method described in Section 2 and the energy quality of the RDF. From the point of view of the operation of the sorting plant, materials that are economically significant are selected. These materials are also characterised by high calorific value. Therefore, as the rating increases, there is a decrease in RDF quality. The Pearson linear correlation coefficient in this case is $R_{xy} = -0.732$. Again, the value of the coefficient may seem relatively low, but this is mainly due to the previously described relationship, i.e., uneven focus on selecting all types of plastic. This relationship is shown in Figure 11.

![Regression curve describing the effect of grade on sorting performance.](image)

Figure 11. Regression curve describing the effect of grade on sorting performance.

To sum up the above considerations, the method described hereinabove can be used to evaluate systems differing in the scale of the amount of waste processed and dealing with sorting of different materials. Moreover, the method indicates a significant inverse relationship between the obtained evaluation value and RDF quality. Therefore, it may be applied for multi-criteria process optimisation purposes, e.g., when changing the arrangement of workstations and changing priorities in the context of selected fractions at individual workstations.

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5. Conclusions

Evaluation of the waste treatment system is the subject of current research. There are many one-dimensional methods for its evaluation. Within the paper’s framework, we presented a general method based on fuzzy logic principles for the multi-criteria evaluation of waste treatment systems and their impact on RDF energy quality.
The paper is divided into four sections. Within the first section (introduction), the authors conducted a review of the state of the art in evaluation of waste sorting systems. The conclusions made it possible to identify a research gap. The second part (A fuzzy multi-criteria model for evaluating municipal waste treatment systems) describes a multi-criteria model for evaluating municipal waste treatment systems. The parameters of the fuzzy logic model (membership functions, inference rules and sharpening functions) were defined. For their definition, the opinion of experts was relied upon. In Chapter 3 (Application of the model—a case study), the presented evaluation model has been implemented for the evaluation of the Wrocław sorting installation for selectively collected waste (metal and plastic). In the present paper, we analysed the evaluation of the selected sorting line in seven selected cases (describing one change in the system operation). In the fourth part (Discussion), as part of the application work, estimations of particular parameters of the model were made, and the results were presented and commented on. It was shown that there is a significant relationship between the level of system evaluation and sorting efficiency and an inverse relationship with the level of RDF obtained.

Further work will be carried out to develop a method of configuring the waste processing system taking into account the placement and configuration of technical equipment, as well as the qualifications of the personnel operating the system. Work will also be carried out to develop a method of assigning the selected fraction to a sorting line operator. Guidelines will also be developed for creating a waste stream (in terms of morphology and size) on the sorting line (in conjunction with the qualifications of the sorting staff) that will enable the higher recovery of the desired raw material fraction. We envisage developing the proposed method to include cost considerations.

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