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DEVELOPMENT OF AN INTELLIGENT DECISION SUPPORT SYSTEM FOR WASTE RECYCLING

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Abstract: The aim of this paper is the development and simulation of an intelligent Decision Support System (DSS) in the field of waste recycling. The proposed model integrates the Random Forest algorithm for classification and prediction with an optimization model that minimizes costs and maximizes revenues from the sale of recycled materials. The database provides input parameters (waste type, quantity, processing cost, revenue), while the user interface enables interaction with the system and the generation of recommendations. The simulation was conducted on hypothetical data for three types of waste (plastic, glass, and metal), applying different recycling strategies. The results demonstrate that the DSS model achieves a positive financial effect, as revenues from sales exceed processing costs, with the greatest contribution observed in the case of metal. These findings confirm that the proposed DSS model can provide economically sustainable recommendations for waste management and serve as a foundation for future research that would include additional waste categories, environmental indicators, and logistical constraints.

Keywords: Decision Support System (DSS), Random Forest, Optimization model, Waste recycling

INTRODUCTION

Urbanization, industrialization, and the expansion of consumer lifestyles have created significant challenges in waste management. With the increasing amounts of municipal and industrial waste being generated, it has become evident that traditional sorting and recycling processes are no longer sufficient for efficient and sustainable resource management (Ibrulj et al., 2025; Negreiros Gomes et al., 2023). Sustainable development requires the application of advanced technologies capable of enhancing existing systems, reducing costs, and improving the accuracy and speed of waste separation processes. One promising alternative to this problem is the application of artificial intelligence. Conventionally, the use of artificial intelligence in waste management has been limited to neural networks for predicting daily waste quantities. In contrast, this study builds on the idea of incorporating advances in artificial intelligence into decision-making systems within the recycling process. The objective is to present a decision support model that can simultaneously satisfy diverse societal criteria primarily ecological and economic, while remaining simple to implement.

Waste logistics and sorting often rely on manual or basic automated processes; however, contemporary technology enables the use of machine learning and data analysis to improve performance and precision. Within our system, the optimization model plays a crucial role in decision-making by reducing overall process costs, including logistics, storage, and sorting. This model facilitates the identification of the most efficient routes, resource allocation, and loss reduction, thereby significantly contributing to system sustainability. On the other hand, the use of the Random Forest algorithm for waste separation represents an innovative approach to the automatic recognition and differentiation of small waste components, which is essential for improving sorting accuracy and recycling efficiency.

The development of an intelligent decision support system for waste recycling requires the integration of multiple functional components that enable the collection, processing, analysis, and optimization of data relevant to waste management (Wirani et al., 2024). Accordingly, this study focuses on the design of an innovative DSS that integrates an optimization model for minimizing the costs of the recycling process with advanced algorithms for automatic waste separation (Fernando and Baldelovar, 2022). By combining these methods, the goal is to create an integrated system that is not only technically feasible but also economically sustainable, reducing operational costs and increasing recycling performance. Such a system has the potential to advance the waste management industry, contribute to environmental protection, and promote the principles of the circular economy, thereby addressing contemporary sustainability challenges through the application of advanced technologies. The proposed model encompasses four key components: a database, the Random Forest algorithm, an optimization model, and a user interface. The interactions among these components are defined through bidirectional data flows, ensuring dynamic information exchange and adaptive decision-making.

MATERIAL AND METHODS

In order to improve the waste recycling process, an intelligent decision support system has been developed that integrates machine learning techniques with optimization models. The system architecture encompasses the following key components: a database, a user interface, the Random Forest algorithm, and an optimization model. The graphical representation of the model is provided in Figure 1.

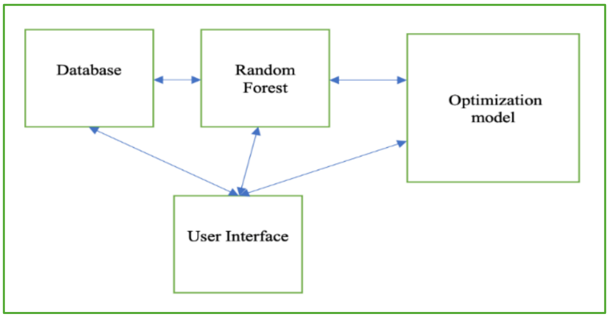

Figure 1. IDSS model, Source: Authors

The database serves as the central repository for storing both input and output information related to waste types, quantities, locations, processing costs, as well as historical data on previous recycling activities. This component enables bidirectional communication with the Random Forest algorithm and the user interface, thereby ensuring the timeliness and relevance of data in the decision-making process (Zhou et al., 2020).

The Random Forest algorithm functions as a mechanism for classification and prediction, employing an ensemble of decision trees to identify patterns within the data. Its application within the system enables:

- classification of waste types according to recycling suitability criteria,
- prediction of optimal waste management strategies based on historical data and
- filtering of relevant inputs for the optimization model.

The algorithm communicates with the database, the user interface, and the optimization model, thereby ensuring multilayered analysis and robust decision-making (Breiman, 2001).

The optimization model utilizes the classification and prediction results generated by the Random Forest algorithm as input parameters for decision-making. The objective of this component is to identify strategies that minimize recycling costs, maximize ecological benefits, and comply with infrastructural and regulatory requirements. The model applies mathematical optimization methods, specifically linear programming, to generate recommendations consistent with defined goals and constraints (Deb, 2001). The objective function can be mathematically expressed as follows:

$$C^r = \bar{n} \sum_{i=1}^{m} \left(\left(\sum_{j=1}^{k} C_{i,j}^{x} r_i \alpha_i x_{i,j} \right) - B_i r_i \alpha_i \right)$$

The objective function is designed to minimize recycling costs while accounting for revenues from the sale of recycled materials. The first term,

$$\sum_{j=1}^{4} C_{i,j}^{x} \; r_i \; \alpha_i \; x_{i,j},$$

represents the total processing costs across all recycling strategies, whereas the second term,

$$-B_i \, r_i \, \alpha_i,$$

reduces the overall cost by incorporating revenues from material sales. In this way, the model balances economic profitability with recycling efficiency.

RESULTS AND DISCUSSION

To verify the proposed architecture of the intelligent decision support system (IDSS) for waste recycling, a simulation was conducted using hypothetical data. The simulation included three types of waste (plastic, glass, and metal), three recycling strategies (A, B, C), and the defined objective function, which minimizes costs while accounting for revenues from the sale of recycled materials.

The simulation was carried out under the following assumptions:

- **Plastic:** quantity 120 kg, processing cost 0.5 EUR/kg, revenue 60 EUR, efficiency 0.9,
- **Glass**: quantity 80 kg, processing cost 0.7 EUR/kg, revenue 50 EUR, efficiency 0.85,
- **Metal:** quantity 50 kg, processing cost 0.4 EUR/kg, revenue 70 EUR, efficiency 0.95.

Selected strategies: Plastic → A, Glass → C, Metal → B.

Table 1. Data for simulation

Waste type	Strategy	Cost (EUR)	Revenue (EUR)	Net cost (EUR)
Plastic	A	0.45	54.00	-53.55
Glass	C	0.51	42.50	-41.99
Metal	B	0.48	66.50	-66.03

Source: Authors

The total net cost amounted to -161.56 EUR**,** indicating a positive financial effect of the system. The results demonstrate that the DSS model successfully integrates classification (Random Forest) and optimization in the selection of recycling strategies. Metal achieved the highest financial effect due to its high revenue and efficiency, while plastic and glass also produced significant positive results. These findings confirm that the proposed model can provide economically sustainable recommendations for waste management, with potential for extension to additional categories and criteria (e.g., environmental indicators, logistical constraints).

CONCLUSION

The simulation of the DSS model for waste recycling demonstrated that the integration of the Random Forest algorithm with the optimization model can provide economically sustainable and efficient recommendations for waste management. The results highlighted a significant advantage of the model, as revenues from the sale of recycled materials exceeded processing costs, which was confirmed in the cases of plastic, glass, and metal. The greatest financial effect was achieved with metal, while plastic and glass also produced positive outcomes.

These findings confirm that the DSS model can serve as a reliable decision support tool under real-world conditions, with the potential to be extended to a larger number of waste categories and diverse recycling strategies. Furthermore, the inclusion of environmental indicators (e.g., CO_2 emissions, material utilization rates) and logistical constraints (e.g., transportation, facility capacities) would enable the development of a multi-criteria model that balances both economic and ecological objectives.

Future research is recommended to expand the model to additional waste types and scenarios; apply advanced optimization techniques (evolutionary algorithms, stochastic optimization) and validate the model using real-world data from local communities. In this way, the DSS model can become the foundation for the development of intelligent waste management systems that contribute to sustainable development and promote the principles of the circular economy.

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