Proposal of waste quality monitoring and contamination detection approach in the context of modern standards and technologies

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Abstract

The paper presents a comprehensive proposal of waste contamination detection approach, with focus on early phases of waste streams. We have systemically analysed current waste quality control procedures in waste sorting centres, commonly used approaches and methods for waste quality monitoring. Based on the current requirements for contamination detection, we have proposed and designed early contamination detection approach, deployed at the beginning of the waste stream. Our proposal outlines the necessary steps to design a state of art detection approach using modern multi sensor detection in combination with artificial intelligence. The focus is given on specifics of contamination detection in different recycled materials, like plastic and paper.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection.

***Key words:** waste contamination, waste quality, recycling, radar technologies, multisensory identification*

Introduction

In recent decades, the topic of waste management has gained strategic importance in connection with the tightening of environmental standards, the growth of production and consumption volumes, as well as the introduction of circular economy principles. Effective waste management is the key to returning secondary raw materials to production, reducing landfilling and CO_2 emissions, and rational use of resources. Modern waste sorting centres face increasing heterogeneity of the waste stream: differences in shape, composition, degree of contamination, and the presence of multilayer packaging complicate the task of automatic identification and separation of fractions.

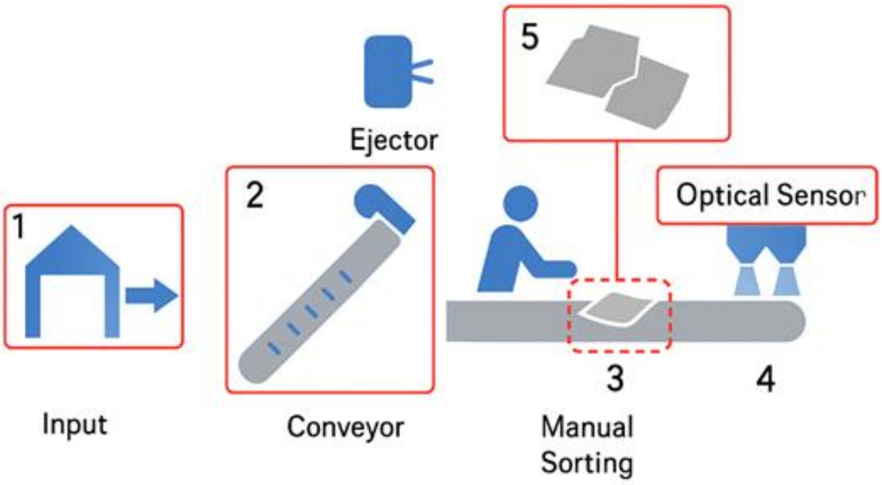

Figure 1: Schematic representation of a typical waste sorting line

Despite the introduction of optical and spectroscopic sensors, the share of unidentified, incorrectly sorted, or completely lost secondary material remains high, especially when processing mixed waste streams (Fig. 1). To achieve the EU's goal of increasing the recycling rate to 65% by 2035 [1], innovative solutions going beyond traditional technologies are needed. The municipal waste recycling rate in Slovakia was 50% in 2022. For comparison the municipal waste recycling rate in Czechia in the same year was 53% and the EU average rate was 49% [2,3,4].

Technological approaches to automatic sorting and material identification

In the last two decades, significant improvement has been achieved in the field of municipal solid waste (MSW) processing and sorting thanks to the introduction of automated systems based on modern sensor technologies and machine vision algorithms. In most sorting facilities (SF), optical sensors, spectroscopic analysers, X-ray devices, and specialized software based on artificial intelligence (AI) are currently used [5,6]. These systems can determine the composition of materials with high accuracy according to colour, spectral characteristics, and geometric features.

The most widespread are combinations of RGB cameras and near-infrared (NIR) scanners, which have been further explored using AI-based sensor-fusion techniques to boost object detection accuracy[7]. X-ray detectors (XRT) are also introduced to solve specific tasks, which can separate metals, glass, and mineral impurities, and in some facilities, hybrid schemes with manual sorting are implemented [8]. Computer vision algorithms, including deep learning methods, have significantly increased the accuracy of recognizing individual waste categories, which has made it possible to automate sorting in large facilities in EU and North American countries.

Despite the successes of recent years, existing technical solutions have several limitations that hinder further improvement of sorting efficiency. One of the main problems remains the inability to identify hidden or multilayer materials, when, for example, a layer of plastic is covered by paper or another opaque component. Modern optical and spectroscopic methods are sensitive to colour and surface contamination but lose information value when working with black, contaminated, or thermally deformed plastic fractions. This leads to significant losses of valuable materials, primarily polyethylene terephthalate (PET) and aluminium, and also increases the amount of manual work in the final sorting stages [9].

A specific problem remains the high cost and complexity of creating universal datasets for training AI systems. Regional specifics of MSW composition require flexible adaptation of algorithms and regular updating of models, which is associated with large time and financial costs. As researchers from Fraunhofer IOSB and several industrial companies (e.g., TOMRA and STADLER) point out, further efficiency improvement is possible only if new sensor principles are introduced that make it possible to obtain data about the internal structure of objects, and not only about their surface properties [10,11].

In recent years, experimental solutions based on the use of lidars and radars, taken from mining, agriculture, and warehouse logistics, have attracted attention. These technologies have the potential to penetrate multiple material layers, identify hidden impurities, and evaluate the physical parameters of objects (for example, density, weight) [12].

However, increasing the number of sensors used leads to a more complex system architecture. It also requires integration and synchronization of data from diverse sources. Additionally, it results in higher implementation costs. It is important to consider not only the technical efficiency but also the economic justification of such solutions, especially under the conditions of the limited budget of medium and small SFs.

Despite significant progress in waste sorting automation, achieving strategic goals such as increasing the recycling rate and reducing negative environmental impact still requires new approaches. These approaches should combine multisensory technologies with intelligent data fusion algorithms (sensor fusion). Solving the task of identifying hidden and complex materials requires the development of adaptive, scalable, and economically efficient architectures that integrate optical, radar, and spectroscopic methods supported by artificial intelligence.

Specific sensor configurations

The most common sensor combinations include:

- **RGB + NIR:** An optical camera and a near-infrared camera make it possible to distinguish most transparent and coloured plastics, and to separate paper from plastic. However, their performance is limited when dealing with black or contaminated materials. They are also unable to detect internal object structures or identify features hidden beneath surface layers. Recent research has also demonstrated that low-cost multi-spectral NIR sensors, combined with deep learning, can provide effective plastic waste recognition with minimal hardware investment, offering a more economically viable solution for smaller facilities [13].
- **Hyperspectral cameras (VIS-NIR-SWIR):** significantly increase the “depth” of spectral analysis, making it possible to identify a wide range of polymers, composites, and even some types of contamination. Limitations are related to the high cost of the equipment and the need for complex calibration [14].
- **XRT:** used for separation by density and structure, it is well suited for removing metals, foreign impurities in glass, and construction waste. A significant disadvantage is the inability to distinguish materials with similar density (for example, certain plastics and organic waste), as well as high requirements for protecting personnel and equipment [8].
- **LIBS/LIFS (laser spectroscopy):** provides the most accurate chemical analysis but requires complex integration and is often inefficient at high stream speeds.
- **LIDAR/3D scanning:** provides precise object geometry, is suitable for shape and size control, helps with spatial separation of fractions, but does not distinguish material [15].
- **Radar systems (FMCW, millimetre band**): rarely used yet, but they can detect the internal structure even under thin layers of material and identify the presence of hidden impurities causing contamination [16].

In modern operations, systems in which multiple sensors work together, and the results of their analysis are combined (sensor fusion) using artificial intelligence are considered the most effective. Such solutions make it possible to increase the reliability of classification even with complex overlaps, the presence of contamination, and high conveyor belt speed. Nevertheless, the main challenges of multisensory systems lie in increased implementation costs, the need to synchronize data streams, demands on computing resources, and operator qualification.

The choice of sensor configuration for a sorting line is therefore the result of balancing requirements for accuracy, speed, economic constraints, and the specifics of the waste stream. The introduction of penetrating sensors, such as radars or lidars, opens new possibilities for identifying complex or masked fractions, but at the same time requires new approaches to processing and merging information – and this forms the core of the architecture we propose.

Proposal of early waste contamination detection

The common approaches to waste quality control detection that are currently used have multiple issues that need to be addressed to improve waste recyclability. Quality control is currently performed only at the waste collection yards and their sorting centres, i.e. quite late in the waste stream, and makes it impossible to identify sources of waste contamination and trace the waste contamination in more detail. Therefore, it is necessary to detect contamination in waste streams as soon as possible, ideally at the origin of the waste stream.

This early detection brings clear benefits across environmental protection, operational efficiency, and regulatory compliance, namely:

- Reduces the volume of contaminated waste sent to landfills or incinerators, instead of material recovery facilities.
- Reduce manual sorting efforts in material recovery facilities.
- Maintain eligibility for subsidies or recycling credits.
- Reduction of loads that must be rejected or surcharged.
- Encourages residents and businesses to participate in proper recycling.

However, early detection requires evaluating the quality of the waste and detecting contamination preferably in waste containers or during waste collection process, which represent the earliest points in the waste stream. Our proposal identified large-volume waste containers in residential areas and waste collection trucks as the most suitable places for early contamination detection. These detection places represent different technological challenges and limitations, compared to traditional detection in waste sorting centres.

Based on the comprehensive analysis of waste quality, waste categories, detection approaches, and AI detection techniques, we have proposed an approach for designing early contamination detection. The central element of this proposal is the integration of multiple sensor technologies into a single adaptive solution. The combination of radar sensors (especially in the millimetre wave band) and optical cameras (RGB/NIR), processed with artificial intelligence, makes it possible not only to identify the surface properties of waste, but also to penetrate beneath the surface and obtain information about its internal structure, composition and density. The radar and camera data are collected, processed, and evaluated in parallel, to allow artificial intelligence methods to fuse the data together and utilise sensors that are more suitable for given detection. This will allow us to improve detection of waste contamination and better evaluate the overall waste quality early in the waste stream.

One of the main limitations of the multi-sensor approach is the high cost of radar and multispectral sensors, which are not always feasible for large-scale deployments. The currently available radar sensor solutions on the market range from 300 € to 30 000 €, depending on their features, detection accuracy, and quality. The ever-changing environmental conditions, like dust, moisture and vibrations can also improve or degrade sensor performance.

The proposal, captured in Fig. 2 as a process diagram, is comprised from three main phases, to ensure the suitability and accuracy of waste contamination detection.

The **first stage** represents a proof-of-concept phase, to evaluate suitability of detection technologies on the different structure of waste, that the waste collection centres are collecting. This step is important, since different centres can have different structure of waste and different types of waste contamination. In the waste collecting centres we have analysed is most of the sorting efforts focused on plastic and paper waste, of which the collecting centres have most valuable information.

To obtain the required data from radar, camera and other sensors, a suitable place must be identified in the waste sorting process, that will not interfere with their sorting operations but will allow us to obtain required sensor measurements. The identified installation place must be able to accompany the sensors as well as required data collection infrastructure and provide the necessary utilities (e.g. electricity and network connection). To keep the infrastructure more compact, a data processing in cloud was utilised, to decrease the computation requirements on site.

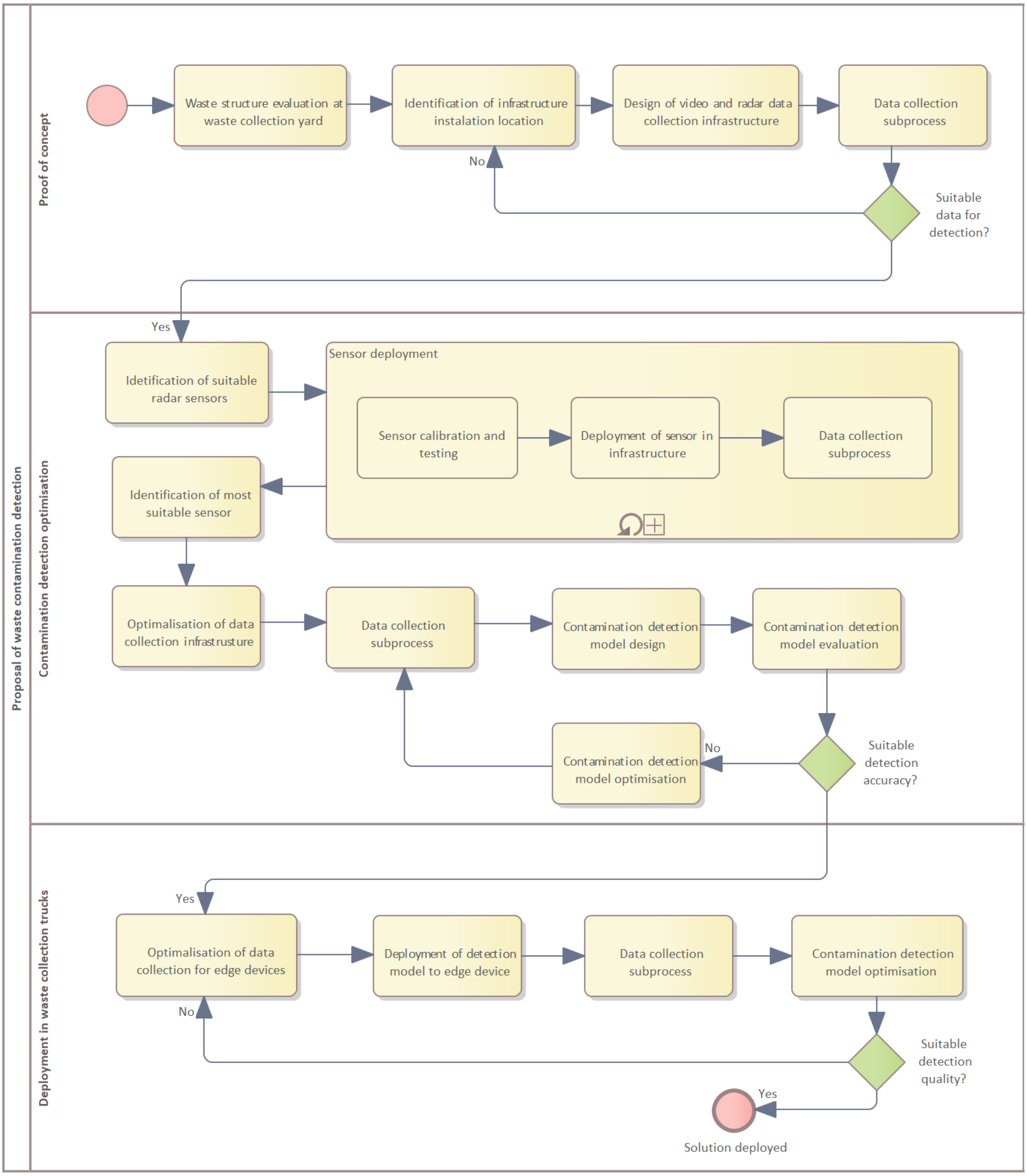

Figure 2: Proposal of waste contamination detection

After the installation of infrastructure, a data collection process must be carried out, to obtain enough data to be able to evaluate suitability of selected sensors, and to obtain data necessary for further evaluation. The combination of radar and camera sensors in our proposal lets us compare radar information with camera images. This allows us to obtain comprehensive data set, that enables radar data evaluation by comparing them with camera data. The duration of data collection should be based on amount and quality of obtained data, where longer collection period can improve the accuracy of gained results. The data collection is carried out in multiple phases of the proposed approach, with very similar steps. The main objective of this subprocess, is to obtain, analyse and evaluate the collected radar and video data, as outlined on Fig 3.

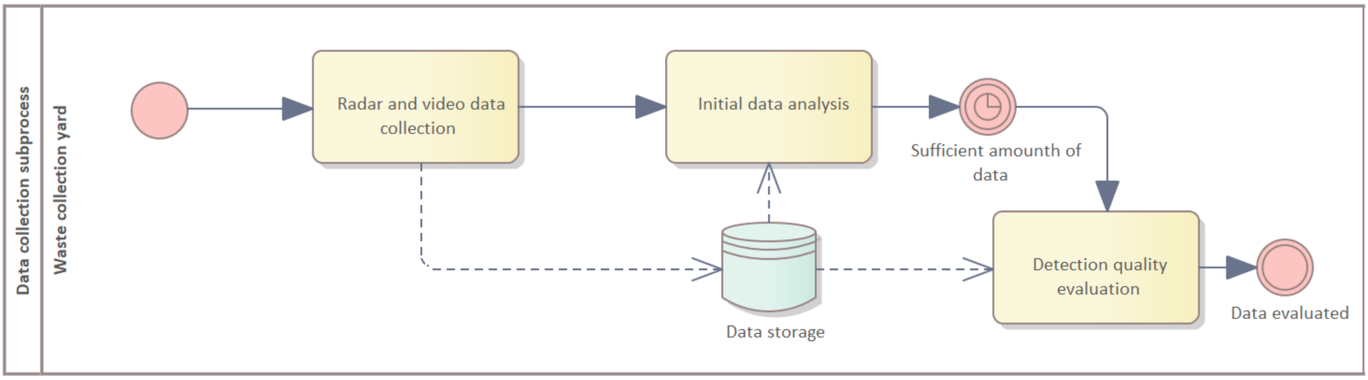

Figure 3: Data collection subprocess

The results obtained from the first phase must be evaluated, based on the suitability of selected sensors for contamination detection and quality monitoring, to ensure usability and practical applicability of developed solution.

The **second stage** focuses on optimisation of contamination detection and quality monitoring, by improving the design from the proof-of-concept phase.

The main focus of improvement is on optimisation of radar and multispectral sensors, whose correct selection can bring major improvements in the accuracy of obtained results. The importance is also given on calibration and fine tuning of radar sensors with variable wave lengths, that can provide different results for different types of waste and their contamination.

Each of the selected sensors must be calibrated and tested in testing environment, and deployed and evaluated in real world conditions, i.e. waste collection centre. The essential part is collecting data from these sensors, to be able to evaluate and compare them.

Based on the individual sensor's performance, an identification of the most suitable ones should be carried out, to identify sensors, or sensor combinations providing best accuracy of contamination detection. Deployment of these identified sensors must be hand in hand with modification and optimization of data collection infrastructure, since the mounting plates and preferred measuring positions can differ between sensors.

Although the selected sensors were used in data collection process, and we have obtained data from these evaluation deployments, due to the modifications in data collection infrastructure a new data collection process should be carried out. This will allow us to improve the overall quality of the data set, and its suitability for detection using machine learning and artificial intelligence methods.

Based on this collected data set a contamination detection model must be designed and evaluated. In our analysis we have identified multiple open-source detection models used in this area, as well as multiple commercial solutions. These will serve as a basis for our contamination detection model. Since different models and approaches can yield different results, a detection model optimisation should be carried out, to achieve suitable detection accuracy.

After achieving sufficient accuracy of our detection model, the designed system must be scaled down for deployment at the beginning of the waste stream.

Therefore, the **third stage** focuses on deployment of contamination detection in large-volume waste containers in residential areas or waste collection trucks.

Deployment of detection in identified areas requires to solve technological challenges, to achieve accurate a robust contamination detection. Therefore, it is necessary to utilise edge devices, that provide suitable computation performance for the required detection. Allthrough the model design requires significant computation capacity for learning, the learned model can perform detection with low power requirements, ideal for deployment on battery powered edge devices.

The infrastructure required for model optimisation differs from the infrastructure required in the final deployment. These modifications must be carried out carefully, with focus on optimal measurement requirements gained in previous phases. These steps are important to significantly accelerate the measured and analysed data quality, required for the final deployment evaluation and optimisation. Due to the different changes to the collection infrastructure and model optimisations, it requires to collect new sets of data, since obtained parameters can differ from data in data sets collected in previous phases, making them incompatible with each other. The successful deployment requires achieving suitable detection quality and accuracy, to be able to detect contamination and monitor waste quality.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection. Attention will be given on precise calibration and configuration of radar sensors, unification of radar and video data and development of a artificial intelligence model for the complex detection of waste contamination with high accuracy and reliability.

The proposed solution is suitable for modern waste quality management, providing high degree of automation with improved decision support of waste streams. By integration with a higher-level system, it could serve as a tool to ensure compliance with environmental regulations, thereby contributing to more efficient, sustainable, and documentable waste management required in modern Europe.

Conclusions

The quality monitoring of waste is today a key condition for achieving the strategic goals of the European Union in the field of circular economy and recycling. Under the conditions of rapidly increasing requirements for the purity level of secondary materials, especially plastics, the importance of a comprehensive approach to quality control in all phases of the sorting process is growing.

This paper presents a proposal of waste contamination detection approach, as part of the waste quality management. We have systemically analysed current waste quality control procedures in waste sorting centres, commonly used approaches and methods for waste quality monitoring. Based on the current requirements for contamination detection, we have proposed and designed early contamination detection approach, for deployment at the beginning of the waste stream. Our proposal outlines the necessary steps to design a state of art detection approach using modern multi sensor detection in combination with artificial intelligence. The focus is given on specifics of contamination detection in different recycled materials, like plastic and paper.

Our proposal creates a basis for a future research and development phase focused on creating an adaptive contamination detection system that will combine radar and camera data with artificial intelligence detection. The proposed solution is suitable for modern waste quality management, providing high degree of automation with improved decision support of waste streams. By integration with a higher-level system, it could serve as a tool to ensure compliance with environmental regulations, thereby contributing to more efficient, sustainable, and documentable waste management required in modern Europe.

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Návrh prístupu k monitorovaniu kvality odpadu a detekcii kontaminácie v kontexte moderných štandardov a technológií

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Súhrn

Článok predstavuje komplexný návrh prístupu k detekcii kontaminácie odpadu so zameraním na skoré fázy zberu odpadu. Systematicky sme analyzovali súčasné postupy kontroly kvality odpadu v triediacich strediskách odpadu, bežne používané prístupy a metódy monitorovania kvality odpadu. Na základe súčasných požiadaviek na detekciu kontaminácie sme navrhli a vytvorili prístup k detekcii kontaminácie na začiatku toku odpadu. Náš návrh zahŕňa potrebné kroky na návrh najmodernejšieho prístupu k detekcii s využitím modernej multisenzorovej detekcie v kombinácii s umelou inteligenciou. Dôraz sa kladie na špecifiká detekcie kontaminácie v rôznych recyklovaných materiáloch, ako sú plasty a papier.

Náš návrh vytvára základ pre budúci výskum a vývoj zameraný na vytvorenie adaptívneho systému detekcie kontaminácie, ktorý bude kombinovať radarové a kamerové údaje s detekciou pomocou umelej inteligencie.

Kľúčové slová: *kontaminácia odpadu, kvalita odpadu, recyklácia, radarové technológie, multisenzorická identifikácia*