# E-Waste Management in Serbia, Focusing on the Possibility of Applying Automated Separation Using Robots

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# E-Waste Management in Serbia, Focusing on the Possibility of Applying Automated Separation Using Robots

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**Abstract:** To encourage proper waste management for electrical and electronic devices (e-waste), it is necessary to invest heavily in the development of recycling technologies. One way to improve the process is to automate separating the shredded parts of e-waste using a robot. This paper's literature review, utilizing the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework, showcases potential robotic technologies for e-waste separation. However, the intricate design of these devices can pose significant challenges in their implementation. Various legal, organizational, and sociological obstacles have left Serbia's e-waste management practice underdeveloped, resulting in an unsatisfactory recycling rate. In this paper, we examined the possibility of using robots in the precise example of recycling refrigerators in a recycling center in Eastern Serbia, concluding that such a solution would have multiple positive effects, both on the employees and the working environment, on the operations of the recycling center itself, and on increasing the e-waste recycling rate in the country.

**Keywords:** recycling; e-waste; robot; waste separation; circular economy



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## 1. Introduction

According to the Waste Management Program in the Republic of Serbia for the period 2022–2031, as stated in the "Official Gazette of the Republic of Serbia", No. 30/18, one of the goals is to reduce environmental pollution by reducing the amount of waste and developing a circular economy [1]. The management of waste from electrical and electronic equipment (e-waste) represents a significant challenge and an obstacle to Serbia's implementation of the circular economy. Rapid technological development and advancement are rendering current electronic and electrical equipment rapidly obsolete, leading to the generation of large amounts of waste. E-waste consists of various household waste devices, such as large and small household appliances, IT equipment, consumer goods for leisure, lighting equipment, electrical and electronic appliances, toys and sports equipment, medical aids, vending machines, monitoring and supervision instruments, etc. [2]. This waste initially falls under municipal waste and makes up 5.7% of the average morphological composition of mixed municipal waste in the Republic of Serbia [1]. In the Waste Catalog, this waste is classified into two groups [3]:

- Group/subgroup 16 02: waste not otherwise specified in the catalog/waste from electrical and electronic equipment: of the eight listed types of this kind of waste, as many as six are marked as hazardous waste.
- Group/subgroup 20 01: municipal waste (domestic waste and similar commercial industrial waste), including separately collected fractions (exception 15 01)—where 14 types of hazardous waste are located, with emphasis on discarded electronic and electrical equipment containing hazardous components.

Therefore, we can conclude that most e-waste possesses hazardous waste characteristics and requires special management. This waste may contain a large number of hazardous elements, such as heavy metals, brominated flame retardants, chlorofluorocarbons, etc. [4]. As the Law on Waste Management requires ("Official Gazette of the Republic of Serbia" no. 36/2009, 88/2010, 14/2016, 95/2018—other law, and 35/2023), this waste must not be mixed with other waste. The disposal of this waste is prohibited without prior treatment, and records of waste quantities and recyclable components are mandatory. This waste is managed by special waste flows, and special measures are in place for collection, transport, storage, treatment, reuse, and disposal [5]. Against these facts, e-waste represents a rich source of resources that can be reused and recycled. The recycling of e-waste has spawned a new industry trend popularly referred to as "urban mining" [6]. There is even 100 times more gold in 1 ton of smartphones than in 1 ton of gold ore, while in 1 ton of motherboards, there is up to 800 times more gold than in 1 ton of gold ore [7]. According to estimates, recycling all of the world's e-waste could meet up to 95% of the global needs for as many as 60 metals, including copper, gold, silver, and platinum [8,9]. Despite these facts, only 17.4% of this waste is fully recycled globally [10].

The aim of this paper is to:

- Review waste separation technologies using robots using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework;
- Analyze the existing practice of e-waste management in the Republic of Serbia with key problem and solution identification in legislation, infrastructure and social behavior;
- Examine the possibility of using robots in the e-waste separation process in Serbia in the specific example of the "E-Reciklaža" recycling center in Niš, Serbia, which will include technical and economic feasibility, expected benefits and potential challenges.

By understanding Serbia's approach to e-waste management, with an overview of all obstacles in the system, international companies which are trading in Serbia can improve their strategies for responsible e-waste management. A detailed description of the current state of e-waste management in Serbia will give recommendations for efficiency, policy, infrastructure, education, and technology improvements. The case study of using robots in the e-waste separation process will be based on a particular case of company E-Reciklaža as a representative of the industry, but similar solutions can be applied to all e-waste recycling centers in Serbia with similar conclusions and impact. Other companies and countries that are dealing with similar problems can learn from Serbia's case.

## 2. E-Waste Management System

In the overall e-waste management system, there are several mandatory steps [11,12]:

1. Collection—carried out at the place of origin.
2. Sorting—involves sorting according to the categories of waste from electrical and electronic devices, and can be performed at the household level, at the local community level, at the landfill, or at recycling centers.
3. Separation—includes shredding, separation of recyclable from non-recyclable parts, and separation of useful components by one of the usual separation methods. The final quality of the recyclate depends on the efficiency of this step.
4. Final processing—involves the processing of previously separated recyclable materials by hydrometallurgical or pyrometallurgical process.
5. Disposal of non-recyclable parts of e-waste.

In order to encourage the development of the circular economy and recycling, it is most expedient to influence the key step, which is the separation of e-waste. Waste separation has numerous positive effects, with the most important one standing out [13].

- Reducing the amount of waste;
- Extending the exploitation life of the landfill;
- Controlling the management of hazardous waste, which is separated from nonhazardous waste in a timely manner by proper sorting;

- Increasing the efficiency of recycling;
- Overall environmental protection.

The separation of waste can be performed manually or automated, whereby automation can be direct or indirect [14]. Manual separation of waste is based on macroscopically observable differences between recyclable waste components. Direct automated separation techniques are based on concentration methods that primarily originate from mining and use the preparation of raw mineral materials, methods such as gravity, magnetic, electric, and flotation concentration [15,16]. Indirectly automated separation is based on the use of artificial intelligence and sensors to recognize certain types of waste [17]. "Macro sorting" refers to the separation of components, items, and packaging from the waste without any special pretreatment. "Micro sorting" occurs when the waste undergoes prior shredding to enhance its surface area relative to its volume [18].

Of all the listed techniques, manual separation is considered the most precise, but not the most efficient, given the high risk of injury and high labor costs [19]. Manual separation is twice as cheap as automated separation, but automated separation can pay for itself three times faster than manual separation [20]. With the rapid advancement of technology and the emergence of innovative technological solutions, an automated technique for efficient waste separation has emerged, involving the use of robots. The integration of robots into the e-waste management system is a significant step towards achieving the goals of the circular economy, and the benefits of switching from a manual to a robotic waste separation system are numerous, including the reduction in illnesses and injuries at work, the acceleration of the separation process, the reduction in costs, the increase in recycling efficiency, the long working life of robots, and so on [21].

## 3. Review of Papers Dealing with the Application of Robots in Waste Separation

### 3.1. Selection of Papers

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol was used for the preparation of the literature review of this paper [22]. The papers were collected from the Scopus and Web of Science databases. Both sources were searched separately. When searching for papers, the keywords "e-waste", "robots", and "artificial intelligence" were used in different combinations, with the help of Boolean operators "AND", "OR", and "NOT". Filters such as "full-text only" and "English language" were applied. Only papers published in a journal or at a conference were included. In the PRISMA diagram, the number of publications for each database is entered individually, as is the total number of papers obtained after applying all criteria in the left cell at the top of the diagram (Figure 1).

Following the PRISMA protocol, we eliminated duplicate publications in the next step and collected the remaining publications from the Scopus and Web of Science databases. Next, we excluded papers that were not available (they were not open access nor did we have institutional access to them without an additional fee) and those that, upon reviewing the title and abstract, did not align with the research objective. After reading the remaining papers, out of the initial 412, only 10 papers were included in the literature review. In the conducted literature search, according to the given criteria, keywords could appear anywhere in a paper, including the literature review. This resulted in a significant number of irrelevant papers, which were excluded from the research. Table 1 shows insights from the selected papers.

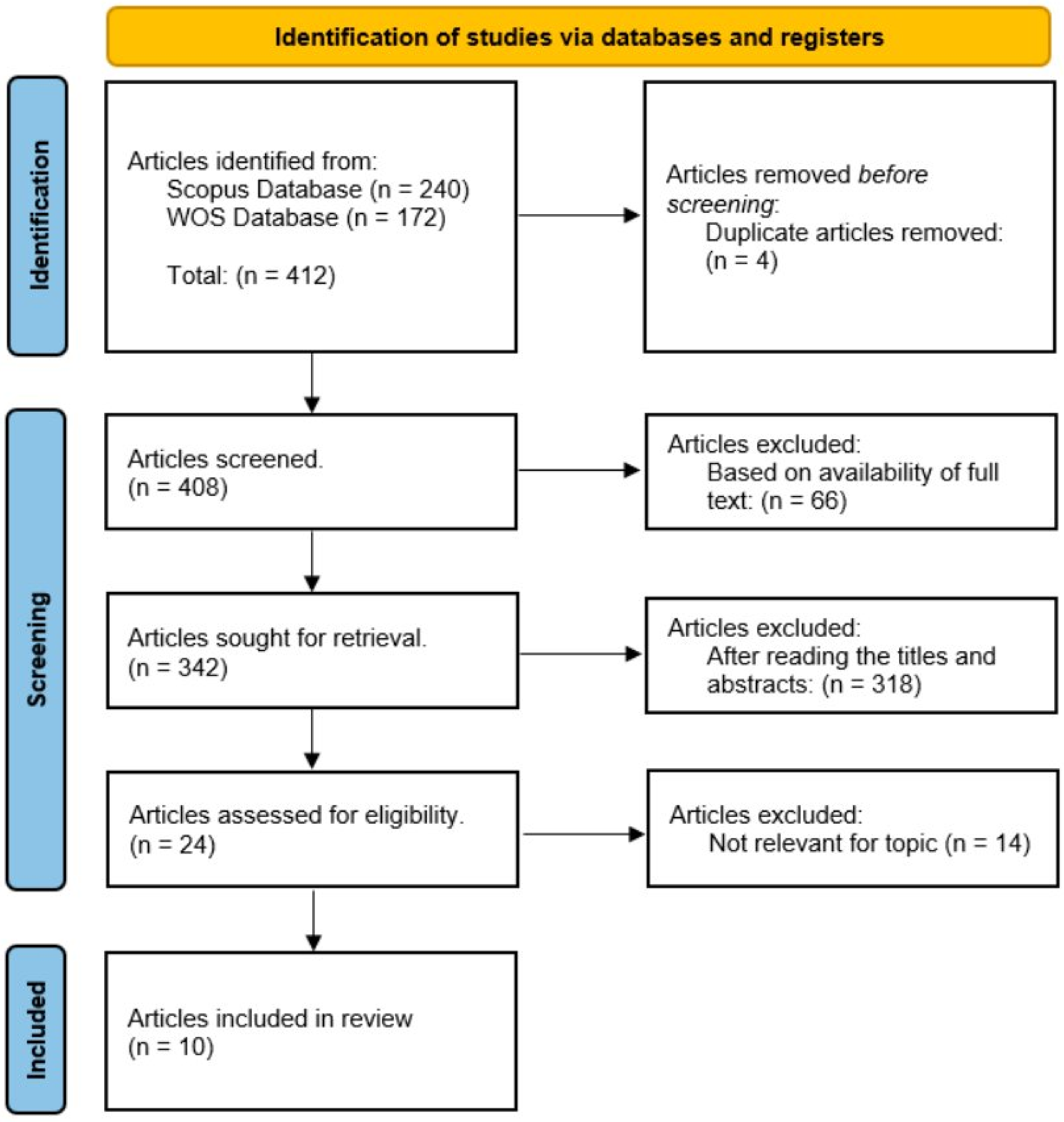


**Figure 1.** PRISMA flowchart showing final results [22].

**Table 1.** The insights from the selected papers.

| Reference | Country of the First Author | Insights |
|---|---|---|
| 1. Kiyokawa et al., 2022 [23] | Japan | • The survey discusses difficulties in waste sorting automation for mixed industrial waste.<br>• It provides an overview of robotic sorters' challenges in grasping, sensing, and trajectory planning. |
| 2. Merdan et al., 2010 [24] | Austria | • An ontology-based system integrates multi-agent machine control and vision-based, real-time path planning.<br>• It enables autonomous disassembly operation coordination with vision system coupling. |
| 3. Bogue, 2019 [25] | United Kingdom | • An overview of commercially available robotic systems for waste sorting and disassembly.<br>• AI-enhanced robotic systems are playing a growing role in the sorting of municipal and industrial waste, prior to recycling.<br>• Delta-robot-based systems can achieve pick rates of 60–70 items/min. |
| 4. Alvarez-de-los-Mozos and Renteria, 2017 [9] | Spain | • The study emphasizes the importance of human–robot collaboration in WEEE recycling and process optimization.<br>• The integration of cobots leads to a higher degree of material recovery and separation, which results in better economic performance compared to traditional manual processes. |
| 5. Shahab et al., 2022 [26] | Saudi Arabia | • This study reviewed 40 studies from 2019–2021 on deep learning in solid waste management.<br>• Deep learning can detect and sort different types of solid waste. |

**Table 1.** *Cont.*

| Reference | Country of the First Author | Insights |
|---|---|---|
| 6. Sharma et al., 2023 [27] | India | • Computer vision technology can significantly improve the management of electronic waste.<br>• The technology aids in automating processes such as identification, classification, sorting, and monitoring of e-waste, reducing human intervention, processing time, and costs. |
| 7. Deng et al., 2024 [28] | China | • Optimizing image capture through predictive exposure control using deep learning techniques improves the visibility and accuracy of robotic operations in disassembly tasks.<br>• The method leverages predictive learning to adapt exposure settings dynamically, resulting in better image quality and more reliable disassembly outcomes. |
| 8. Nafiz et al., 2023 [29] | Bangladesh | • A remotely controlled system that aims to improve urban waste management through automation and deep learning, using deep convolutional neural networks (DCNNs) and image processing techniques to accurately classify different types of waste, was studied.<br>• The ConvoWaste deep learning model system achieved a high level of accuracy, with the deep learning model reaching a 98% accuracy rate in waste classification tasks. |
| 9. Ramadurai et al., 2022 [30] | Chicago, USA | • Human involvement increases robot accuracy in recycling tasks.<br>• Human assistance improves robot accuracy significantly in diverse material sorting.<br>• Different levels of human involvement in human–robot collaboration is suggested. |
| 10. Chen et al., 2022 [31] | Florida, USA | • The introduction of collaborative robots (cobots) can significantly reduce the physical and cognitive workload of human workers during e-waste disassembly and improve ergonomic conditions for workers.<br>• Proper training for human workers on how to interact with cobots is crucial for safety and optimal task allocation between humans and robots.<br>• Robots are better suited for tasks that require precision and strength, while humans excel in tasks that require flexibility and problem-solving skills. |

### *3.2. The Major Findings of the Selected Papers*

Unlike classic production facilities, recycling facilities operate without production deadlines, instead processing all waste according to a combination of additional financial and technical criteria. When recycling, you should take into account the waste that is in the recycling plant, the space it occupies, as well as the composition of the components from which it is made, because they directly affect the value of the recycled raw material and can dictate what will be recycled from the collected waste. This indicates that the recycling process, and therefore the separation process, is a non-uniform and complex task that is currently impossible to completely automate.

A typical example of the automation of the waste separation process is based on the combination of a robot and a vision system in a recycling plant [23]. One of the possible approaches when it comes to the automation of recycling with the help of robots is the application of a hybrid approach, where humans can be included in the automated process and can add additional quality through their cognitive abilities [24]. There are already commercially available robotic recycling solutions on the market, which can sort different materials from waste, such as ZenRobotics, SamurAI robot, Max-AI AQC, and installed Liam robot systems developed by Apple to disassemble their devices [9,25].

Robotic waste separation systems can be divided into two main subsystems that affect the separation process and its success [23]:

- Vision systems and artificial intelligence algorithms.
- Robotic systems with grippers.

Vision systems and the application of machine learning and artificial intelligence aim to recognize an item to be recycled from the waste process [26–30]. Recognition is performed by applying algorithms that are trained on a training set to recognize and classify a specific type of waste or element. The success of detecting recycling objects depends on the performance of the vision system, algorithms, and training set. Certain databases are available for training recognition algorithms that also contain e-waste data, but as e-waste is very diverse, often the database of one case cannot be generalized and applied to others [23,26,29].

The main components of the vision system are [26,29]:

1. Sensors: most commonly cameras and/or optical sensors.
2. Image processing hardware: consists of processors (e.g., microprocessors, a Digital Signal Processor (DSP), and a Field Programmable Gate Array (FPGA)) that enable fast processing of captured images and memory that serves to temporarily store data during image processing.
3. Image processing software, which can be separated into two parts:
   (a) Image analysis algorithms that include algorithms for filtering, segmentation, pattern recognition, classification, and other visual data processing;
   (b) Machine learning and artificial intelligence, where algorithms are developed that use deep learning techniques to recognize and interpret complex visual patterns.

There are multiple reasons that make the application of computer vision in e-waste recycling highly desirable, such as the following [27]: reduction in overall recycling costs, speeding up the process, easier process control, centralized database, real-time information, quality control, high precision, etc.

A robot system with grippers assigns the robot the task of selecting an item for recycling, sorting it, and disassembling it, either independently or with human assistance. The robotic system's performance influences the speed and precision of the separation process, while the gripper selection determines the reliability of grasping the object. The choice of grippers is large and depends on the shape and dimensions of the object being recycled (e.g., two-finger, vacuum, multi-finger, or usage of multiple grippers) [23].

The development of new technologies, like the collaborative robot, holds significant potential for use in recycling and waste separation, leveraging the cooperation between humans and robots, a concept known as human–robot collaboration (HRC). HRC makes it possible to use the strength, precision, and speed of the robot, while on the other hand, humans can contribute with cognitive abilities that the robot cannot fully replicate (e.g., skills, experience, creativity, etc.) [24,30,31].

According to Ramaduarai et al. [30], it was established that the speed of recycling and the success of catching objects increase depending on the level of human involvement in the waste separation process, and that recycling is globally faster than when only a human or a robot work independently. Human involvement can be divided into three levels, where each level of involvement implies previous levels [30]:

- Level 1: Occlusion removal—removing objects that overlap other objects makes it easier for the vision system to recognize objects and capture them later.
- Level 2: Optimal distance—moving the object to allow enough space for the robot's gripper to grasp the object.
- Level 3: Optimum Grasping Position—placing the item to be sorted in a position that is ideal for grasping by the robot.

## 4. E-Waste Management in Serbia—Current Situation

In Serbia, there is still no systematically organized separate collection and sorting of e-waste, where e-waste should be collected under the supervision of local communities as a special waste process. However, the practice is such that the organized collection of this waste occurs only sporadically [1]. Given that e-waste can have the character of hazardous waste, it should be disposed of either in hazardous waste landfills or neutralized before disposal. Contrary to these facts, this waste most often ends up in municipal waste landfills, together with other waste [32]. During 2022, according to data from the Serbian Environmental Protection Agency, 22,571,038 items of electrical and electronic waste, or 20,226.6 tons, reached the market. In the same year, the reuse of 30,316 tons of e-waste was recorded, while 3451 tons of separated components from this waste were exported, of which 2574 tons had the character of hazardous waste [33]. Based on the reported data, it is estimated that the average amount of collected e-waste is 6.3 kg/inhabitant annually, which is unsatisfactory. There are estimates that 15,000 tons of this waste will be collected in 2024, that is, 38,000 tons in 2031 in Serbia [1].

There are around 500 operators licensed to collect e-waste in Serbia, and the collection is based on the selective collection of profitable waste. In Serbia, only 5 operators engage in e-waste recycling, 13 operators focus on reuse, 10 operators handle hazardous waste treatment, and 89 operators handle non-hazardous waste from electrical and electronic equipment. Not a single operator in the entire territory of Serbia deals with e-waste disposal [1]. Only in the territory of Belgrade, the largest city in Serbia, are there 58 operators who collect e-waste, while 42 operators, in addition to collection, have storage permits. A total of 34 operators deal with e-waste treatment [34]. According to the interactive map "Where to Recycle", which represents a common social good and provides information on all available collection and recycling centers for all types of waste in Serbia, it can be counted that there are as many as 14 recycling centers that collect and/or treat e-waste [35]. Figure 2 shows the approximate schedule of collection and recycling centers for this waste in Serbia.

In all recycling centers, manual sorting of e-waste according to classes and manual disassembly of macro-components are carried out with the eventual application of magnetic separators for separating ferrous metals and Eddy current devices for separating non-ferrous metals. No center has even considered the use of robots in the separation of e-waste [36].

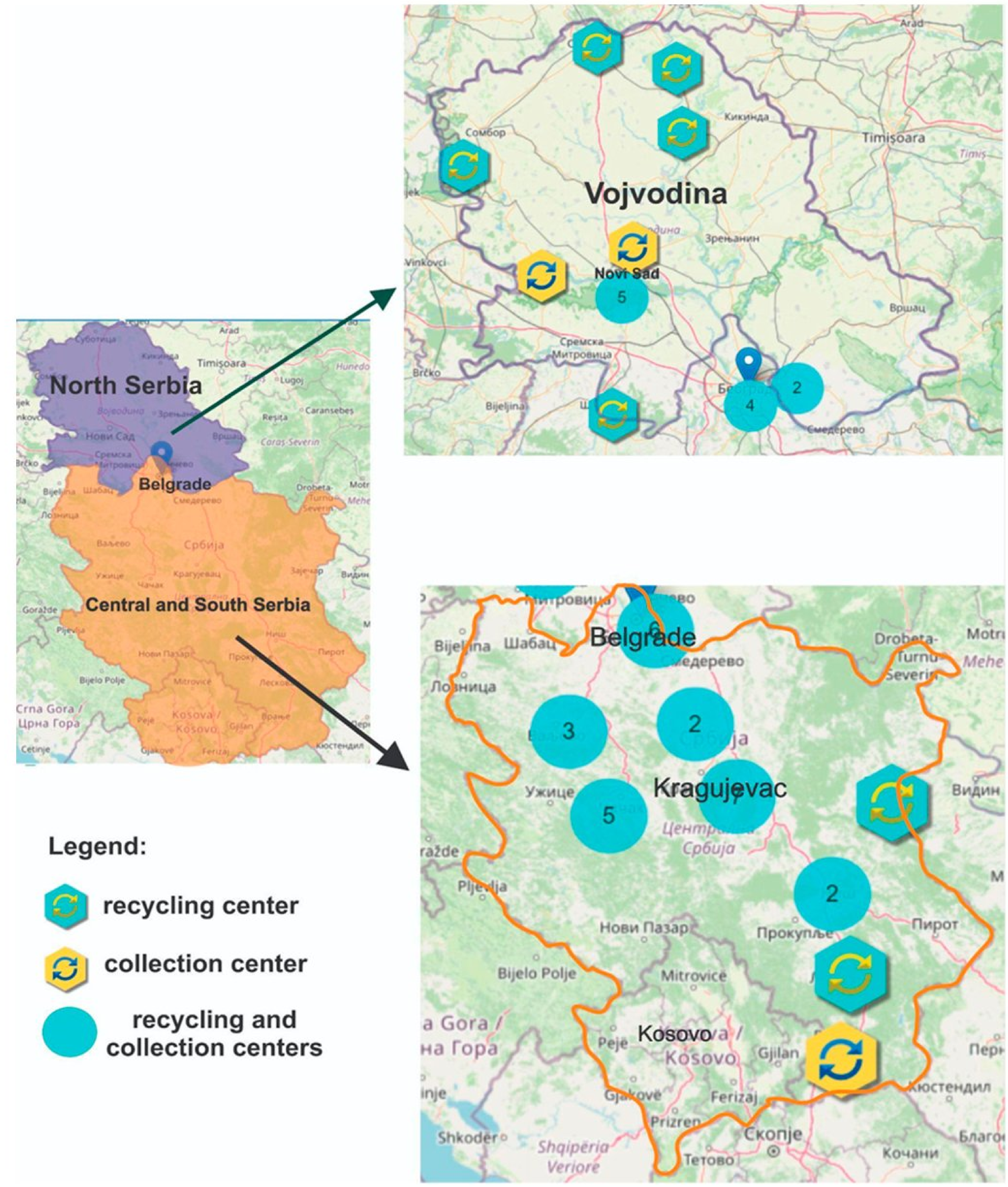


**Figure 2.** Schedule and number of e-waste recycling and collection centers in Serbia [35].

### *4.1. Obstacles and Potential Solutions in the E-Waste Management System in SERBIA*

In 2022, the recorded municipal waste recycling rate in Serbia was 17.7%, which also includes e-waste recycling [37]. Contradictory information indicates that one of the national goals as of 2019 was an e-waste recycling rate of 50–75%, depending on the e-waste category [2]. Clearly, we are not even close to meeting this goal. The reasons for this state of affairs are multiple and can be defined through legal, organizational, and sociological obstacles.

#### 4.1.1. Legal Obstacles

From a legal point of view, a major problem is the inconsistency of the legislation governing e-waste management in Serbia with the legislation of the European Union (EU). According to data from 2021, each EU resident collected an average of 11 kg of e-waste, and the EU recycled nearly 40% of this waste, clearly indicating Serbia's significant lag [38]. The European Directive 2012/19/EU, the umbrella law for regulating the conditions of e-waste management at the EU level, has not updated the national legislation concerning waste management. The umbrella law that regulates waste management in the Republic of Serbia is the Law on Waste Management ("Official Gazette of the Republic of Serbia", no. 36/2009, 88/2010, 14/2016, 95/2018—other law and 35/2023) [5], while the umbrella legal act regulating the management of waste from electrical and electronic devices is the Rulebook on the list of electrical and electronic products, measures prohibiting and limiting the use of electrical and electronic equipment containing hazardous substances, methods and procedures for managing waste from electrical and electronic products ("Official Gazette of the Republic of Serbia", No. 99/2010) [3].

Some of the observed non-conformities are as follows [38–41]:

- The absence of a legal framework for the establishment of collective and individual schemes according to the principle of waste management, "producer responsibility" in Serbian legal acts, as prescribed by Article 5 of Directive 2012/19/EU.
- The absence of a legal framework for establishing a National Register for manufacturers or importers of electrical and electronic equipment in Serbian legal acts, as prescribed by Article 16 of Directive 2012/19/EU.
- The absence of prescribed obligations of separate collection, treatment, reuse, and disposal of e-waste in Serbian legal acts, as provided for in Articles 5, 12, and 13 of Directive 2012/19/EU.
- The absence of a prescribed financial guarantee by the manufacturer or importer of electrical and electronic equipment that they will finance the responsible management of e-waste in Serbian legal acts, as prescribed in Article 12 of Directive 2012/19/EU.
- The inconsistency of prescribed national goals for the collection and recycling of e-waste with European goals, prescribed by Article 7 of Directive 2012/19/EU. Moreover, Serbian legal acts do not define who is in charge of implementing the goals.

Given that Serbia has been a candidate country for EU accession since 2004, a deadline for harmonizing national regulations with European goals concerning e-waste was established as 1 January 2022 [42]. Apparently, that deadline was not met.

#### 4.1.2. Organizational Obstacles

The infrastructure for e-waste management at the state level practically does not exist, and the motivation for e-waste recycling depends to a large extent on the will of a few private companies that deal with it for personal gain [43]. At the moment, communal services typically collect e-waste along with other bulky waste because there is neither a system in place for the separate collection of this waste from households nor locations for its collection at the local community level [44,45]. There are only collection companies dealing with targeted collection of this waste, and there are 15 of them nationwide [35]. These companies are located in urban areas, while there are none in rural areas [36]. The return of waste electrical and electronic equipment from retail establishments is only partially carried out, while these same retail establishments do not offer the service of accepting this waste from citizens [41]. This is because those who collect this waste should have a storage permit according to the Law on Waste Management, and currently only companies dealing with the collection and recycling of e-waste in Serbia have it [46]. Practice has shown that even the companies involved in the recycling of e-waste in Serbia are not sufficiently motivated to collect waste directly from households, but do so through occasional environmental campaigns [47]. Currently, the most efficient collection of e-waste in Serbia is carried out through organized collection actions initiated by the recyclers themselves, which include bringing the waste to a specified location or the arrival of collectors at the home address. The biggest problem in the entire e-waste management system is illegal flows, which make monitoring the situation in Serbia and statistical analysis difficult [35,48]. The lack of professional staff for e-waste management in the relevant institutions has been a problem for years. This begins with the Ministry of Environmental Protection, where additional staff are required to handle the implementation of legal and strategic acts. This extends to the inspection supervision sector, which oversees the performance of activities within the framework of e-waste management, and the Serbian Environmental Protection Agency, which is responsible for reporting [41]. Due to the lack of specialized software for monitoring waste flow, operators in Serbia improvise their e-waste reporting methods, primarily using various accounting programs or Microsoft Excel 2021 [49]. The root of these problems lies, to the greatest extent, in high investment costs and the absence of state support. Landfill fees are generally low, making e-waste treatment and recycling operations a priori expensive. Therefore, there has been minimal investment in the development of e-waste separation technologies thus far.

#### 4.1.3. Sociological Obstacles

Sorting all waste, including e-waste, at the household level is almost nonexistent in the Republic of Serbia. This is because this kind of habit and education are absent. Serbia, a country in transition with a low standard of living and a constant tendency toward economic development, does not prioritize environmental protection, as evidenced by the absence of environmental awareness and concern. Environmental awareness develops from a young age and the support of the family and then of educational institutions is needed first, so that pro-ecological habits can become established and become part of "education at home" [50]. According to research on Serbian citizens in 2022, only a fifth of citizens have sufficient knowledge about how to sort waste [51]. In general, the urban population in Serbia, which is supposed to have the most developed environmental awareness among all citizens, has only partial ecological knowledge [52]. Research has shown that the habit of young people in Serbia is to dispose of e-waste without any order, together with other waste or in places that are not even intended for waste disposal, in direct connection with the fact that there are no planned places for e-waste disposal [53]. The citizens of Serbia are not adequately informed about what e-waste is, how to manage it, the benefits of its recycling, as well as the consequences of its improper disposal [54].

#### 4.1.4. Potential Solutions to the Problem

According to the previously exposed problems, the proposed solution primarily involves increasing state support to strengthen the entire e-waste management mechanism. Declarative support alone is insufficient; therefore, financial support for research is also necessary. According to the National Program for the Integration of Serbia into the EU, the process of European integration is based primarily on the transfer and application of EU legislation into the national legislation, the establishment of administrative and institutional capacities with the aim of effective application of European regulations, and the provision of financial and economic instruments [55].

In this regard, the key factors of the improvement mechanism of the e-waste management system would be the following:

- Improving and harmonizing legal acts with European ones, which would make e-waste management strictly controlled;
- Harmonizing e-waste recycling goals with European ones and encouraging intensive engagement in their fulfillment;
- Increasing environmental awareness among citizens of Serbia, through constant education and the implementation of a targeted campaign through the media;
- Incorporating the private sector into the e-waste management system, in order to influence the system through the production of electrical and electronic devices, by incorporating recyclable materials, building recycling facilities and financial motivation by the state;
- Supporting research activities in the field of development of innovative e-waste separation technologies;
- Improving the infrastructure for e-waste management through the provision of all necessary facilities for the collection, transport, and recycling of e-waste.

One of the most effective elements of the previously described mechanism for improving the e-waste management system is the last one: providing the necessary infrastructure for e-waste management. Only concrete action on this element, specifically the automation of the waste separation process using robots, can achieve the set goals of e-waste recycling [56]. Separation of e-waste using robots can primarily be applied in waste recycling plants as a secondary separation line. One of the goals of the Waste Management Program in Serbia is to achieve a 45% e-waste collection rate by 2031 and to establish recycling yards throughout the country, within each municipality, that will be able to accept special waste flows, such as e-waste, while facilities for disassembly and sorting will be established at the regional level. Construction of a secondary separation plant is planned in each regional center [1]. This measure is a good basis for the implementation of automated separation of e-waste using robots.

## 5. Case Study: The Possibility of Using Robots in E-Waste Separation in the "E-Reciklaža" Recycling Plant, Niš, Serbia

E-waste is very demanding and difficult to separate due to its complex construction and the diverse shapes and forms that may occur [57]. Different manufacturing methods characterize televisions and refrigerators, or telephones and microwave ovens, although their composition is similar. It is especially challenging when the devices are bulky and difficult to manipulate, because then it is necessary to apply mechanical force to shred them. This results in chipped parts of irregular shape and sharp edges that are difficult to detect and manipulate. For these reasons, a unique template cannot be applied when separating e-waste, nor can the separation process be fully automated [27,58]. In this paper, the possibility of separating refrigerators using a robot was investigated in the concrete example of the recycling center "E-Reciklaža", which is located in Eastern Serbia, in Niš. Since 2010, "E-Reciklaža" has been one of the leading companies in the field of e-waste recycling in Southeast Europe. The company's main activity is collecting, transporting, storing, and treating e-waste [59].

### *5.1. Description of the Refrigerator Recycling Procedure in the Recycling Facility "E-Reciklaža"*

Machine recycling of refrigerators is conducted in seven steps, as shown in Figure 3 [60]. The first step involves delivering the material for recycling to the "Querstromzerspaner" (QZ) disintegration device, which has several modes of operation depending on the type of e-waste being recycled. The second step involves preparing the refrigerator by manually removing rubber, wood, glass, styrofoam, cables, and any remaining organic materials. In the third step, gas is extracted from the refrigerator (chloro-fluoro-carbon and hydro-chloro-fluoro-carbon), the compressor is removed and placed on a specially prepared surface, a place for squeezing oil into receiving reservoirs, from which the oil is then poured into metal barrels via a pump. The prepared refrigerator is introduced into the QZ device via the input conveyor. In the fifth step, the input material is crushed and ground with a powerful engine that drives massive chains. In the sixth step, the components are separated into: (1) ferromagnetic materials, (2) non-ferrous metals and plastics, and (3) polyurethane foam. Ferromagnetic materials are separated using an ascending conveyor and a magnetic separator. The non-magnetic residue is transported to the "Eddy Current" device, where non-ferrous metals such as copper and aluminum are separated from other parts, i.e., plastic. It can occur that the fractions recycled separated in this way are not completely clean, so the operator needs to manually remove the remains of plastic from the shredded metal in order to improve the purity of the fractions. This procedure contributes to the recycling process's efficiency by reducing waste and optimizing resource usage. Screw conveyors transfer the material to the "screen machine" after 240 s of treatment. The "screen machine" separates the polyurethane foam from the remaining material at this point. Special "matrices" help treat the polyurethane foam further at a high temperature of 120 °C, ensuring the complete extraction of freon, a crucial step for cleanliness.

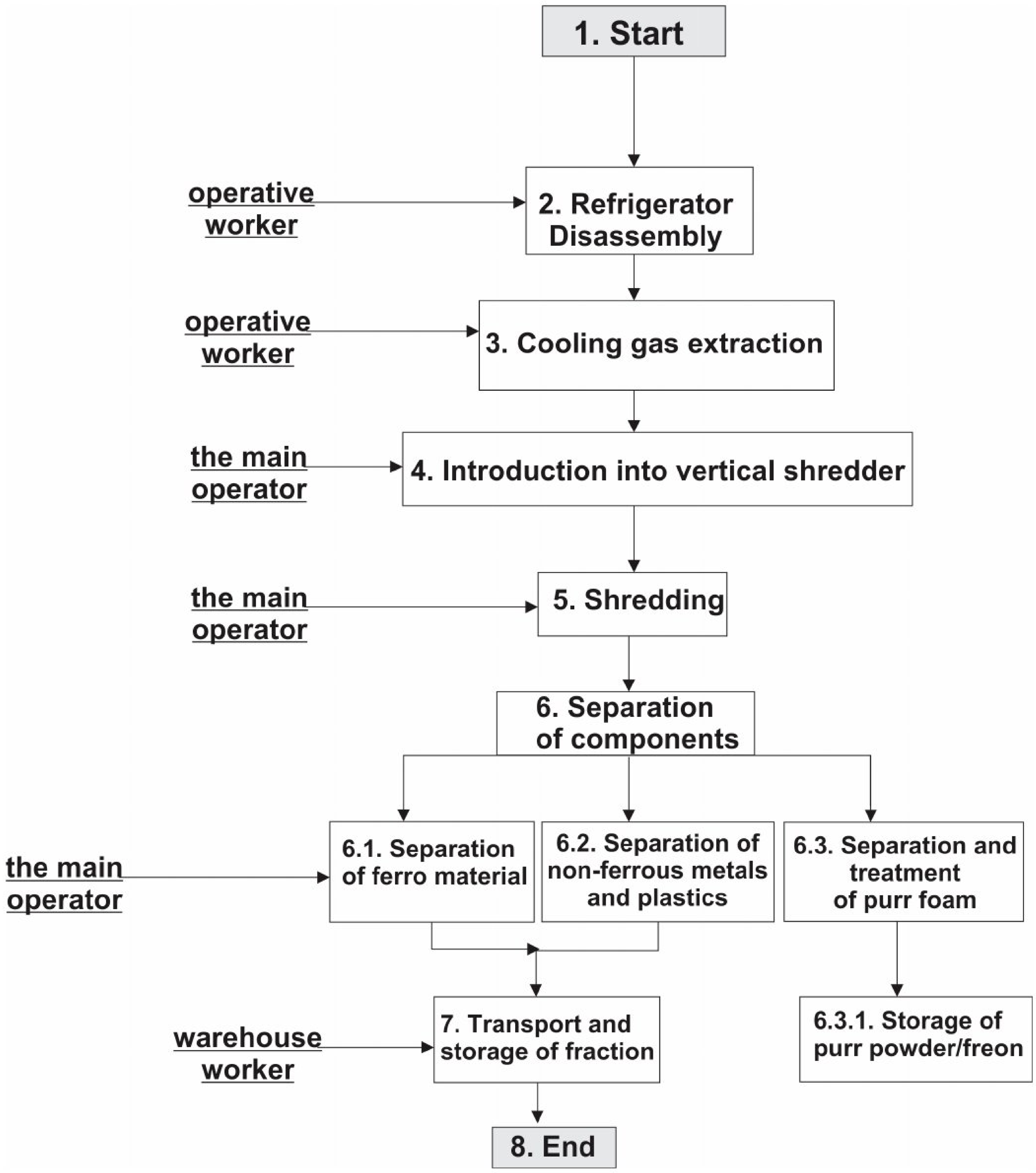


**Figure 3.** Flow diagram of the refrigerator recycling process.

*5.2. Identification of the Steps of the Recycling Process Suitable for Automation/Robotization*

According to Section 5.1, the separation of components, the sixth step in recycling, is best suited for automation and robotization. This step involves "pick-and-place" and manual sorting, currently carried out by 2–4 workers per shift (Figure 4). The environment of this workplace is characterized by the "short burst method of working", during which the workers work at a faster pace, while they typically operate at a slower pace. Recyclable samples arriving on the conveyor belt can be of different sizes and shapes, as shown in Figure 4b, which presents a challenge in terms of capture. Moreover, some parts may contain plastic elements, which visually complicate the task of visual recognition based on colors. The workplace itself requires standing and is quite non-ergonomic, with a high risk of musculoskeletal back injuries due to bending.


**Figure 4.** Manual sorting of ferro-neutral metals (**a**) and recycled samples (**b**).

### *5.3. Technical Requirements Analysis and Proposed Solution*

A typical robotic waste separation setup that can be considered in this case, depicted in Figure 5, comprises a pick-and-place mechanism functioning on a conveyor. Guided by a vision system equipped with one or more cameras and specialized algorithms, the robot identifies image content, locates items, and carries out picking tasks. The effectiveness of waste separation systems heavily relies on the computer vision algorithms' ability to recognize diverse waste types and the robustness of grippers handling a wide range of objects [14,61,62]. For the purposes of this paper, various approaches may be considered, including color, shape, and volume analysis of detected samples, regarding the possible grippers that may be considered.

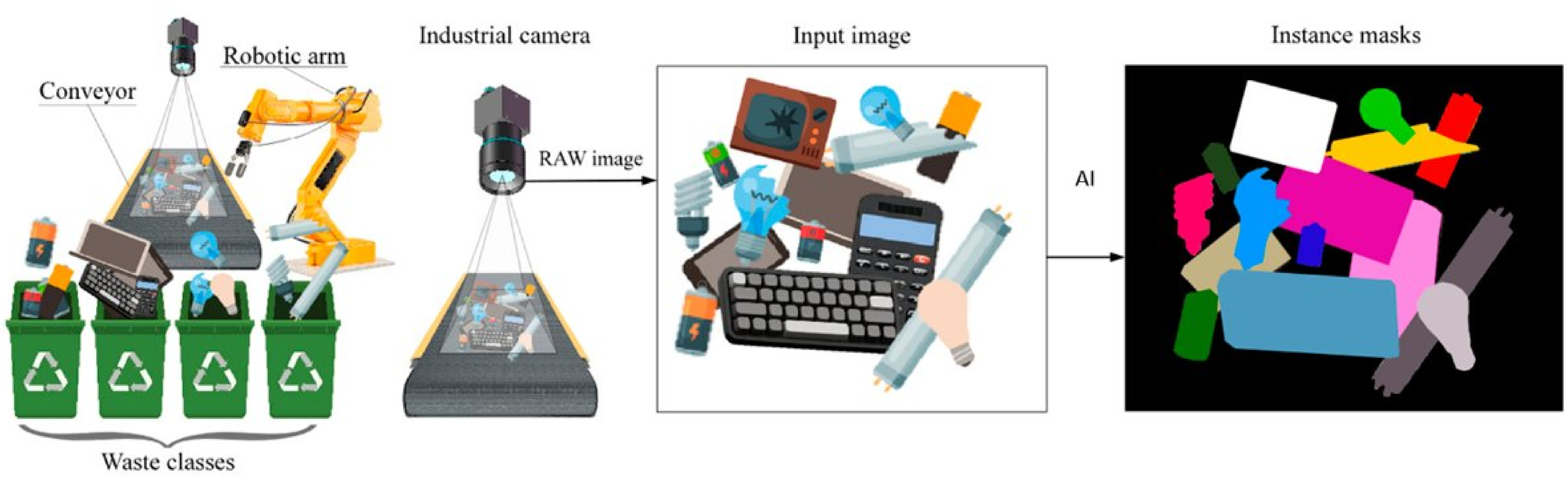


**Figure 5.** A typical robotic waste separation setup.

The technical requirements imposed by the company for the robotized solution are given implicitly through requirements of achieving 95% aluminum purity after sorting and increasing the amount of extracted non-aluminum non-ferrous metals (copper, brass, and zinc) to at least 10%. To meet the requirements, it is necessary to identify crucial aspects which pose challenges towards achieving these goals. The analysis of the current situation considers recycling steps starting just after the Eddy current separator, since all previous steps are overall optimally set to account for the different types of devices which are recycled, and therefore are not subject to alterations.

As mentioned earlier, the conveyor output is not consistent in volume due to the discrete nature of the QZ device input. Consequently, the input and output of the Eddy current separator, which follows the QZ processing, are not consistent as well. As a result, the Eddy current separator output conveyor's uneven distribution of material in a single layer presents challenges for both machine vision and object picking operations. One possible solution to a given situation is the introduction of a set of rotary brushes moving in the opposite direction from the conveyor, as well as a vibrating section of the conveyor to ensure an even single-layer distribution.

A camera vision system could be used to detect non-aluminum parts on the conveyor and guide the robot to pick them. Initial tests performed on the test sample from the recycling center using an AI algorithm indicate very good classification results with 97.6% objects correctly classified non-aluminum parts. However, the facility in which the sorting is performed features a lot of natural light in addition to the artificial lighting, which may lead to incorrect part position identification due to inconsistent shadow and shine occurrence. To mitigate the sensitivity of the proposed vision system to light conditions and increase its robustness to external/ambient light conditions, it is recommended to shield the detection area from ambient lighting and use only artificial lighting.

To understand the challenges related to robotized picking, the following analysis of the hardware requirements relies on the statistical data gathered from the process of recycling refrigerators. In the particular analyzed case, the QZ device outputs up to 20 t per 8 h shift, and up to 5% of the output is a mix of non-ferrous metals. Within the mix, at least 85% is aluminum, which leaves up to 15% of material that needs to be extracted from the conveyor. The observed sample had an average weight of 5,14 g, accounting for 98% of the total mass of pieces that required extraction, with the largest overall sizes ranging from 5 mm to 50 mm [60]. According to the sample's statistics, there are typically 1.013 pieces to pick every second or one piece every 0.9869 s. The layout of the conveyor and depositing trays is such that the pieces' depositing positions are less than 300 mm away from the furthest picking position. The determined payload, working range, and speed indicate that different robots in delta or SCARA configurations can be used. Given that orientation does not matter when picking or depositing the pieces, and considering the plant's spatial requirements for overhead mounting, we selected a delta robot configuration for further analysis, as this configuration typically achieves the 0.3 s standard cycle time that most robot manufacturers claim [63]. Although the coolant and/or purr-powder generally do pose a risk for explosion, they are extracted in an inert environment in steps prior to the sorting conveyor belt, and therefore the robot is not required to have ATEX rating. To protect from the remaining purr-powder, a typical IP 65 level is adequate for the robot and its controller.

The choice of an appropriate gripper, capable of handling a wide variety of shapes and sizes of pieces, is the challenging physical aspect of the separation process. The QZ machine's shredding process often results in numerous pieces with folds, creases, and twists. The required gripper activation and deactivation time, varying thickness, and possibility of deformation imply that the choice of mechanical and pneumatic grippers with rigid fingers is not a good one. Given the non-ferrous nature of the observed metals, the same applies for electromagnetic grippers. One possible solution is to use suction grippers with highly flexible lips or vacuum-sponge suction cups, which have the ability to conform to the irregular shapes of the pieces. However, the presence of purr-powder is generally unfavorable for the suction type of grippers due to potential for clogging of the airways. To overcome this issue, the suction gripper needs to be combined with adequate air filtration and/or periodic automatic blow-outs using air streams, which are solutions not uncommon in the wood-processing industry.

In summary, the proposed solution consists of the camera vision system, which recognizes individual non-aluminum pieces on the conveyor belt and forwards their coordinates to the robot. The delta configuration robot, placed on a portal over the conveyor, picks up individual pieces and deposits them into corresponding bins using suction grippers with adequate filtering and cleaning subsystems. Safety fencing encloses the solution and integrates it with adequate safety interlocks and systems to prevent human injury.

The introduction of a highly conservative estimate suggests that the picking and depositing cycle, including gripper activation and deactivation, would take 0.45 s to execute, which is 50% more than the standard cycle time for similar movement. This estimate still leaves potential to double the production output using the same hardware, or to account for other uncertainties and periodic gripper cleaning. The QZ machine dictates the total production output, so the introduction of the robotized solution for non-ferrous metals does not directly affect it, but it does create room for future capacity increases. We can observe the direct benefits of the proposed solution through the prism of improved worker wellbeing and increased quality consistency in the separation process.

The improved separation consistency leads to a higher purity level of the separated material, directly affecting all successive steps of the recycling process and increasing the quality of the recycled material while reducing its carbon footprint. The increased purity of sorted metals leads to direct economic benefits for the company, since sorted metals with purities higher than 95% can be sold at premium prices, whereas they lose 10% of their value for every 10% of additional impurities. Moreover, aluminum, which makes up to 85% of the non-ferrous metals on the line, can be more than five times cheaper than other non-ferrous metals on the line, especially copper and brass. Therefore, improved the sorting of copper, brass, and other metals which are considered as impurities actually increases the price of the shredded aluminum, and also yields higher amounts of more valuable metals. The statistics suggest that fulfilling only the requirement of the 10% increase in non-aluminum part extraction yields approximately a 1.7% purity increase in the shredded aluminum. Therefore, meeting the aluminum purity requirement is more restrictive, and it will automatically lead to the fulfillment of the second requirement. Even with a highly conservative improvement, requested by the company, of only 10% in non-aluminum extraction from the conveyor, compared to current manual sorting, the solution brings significant economic benefits to the company. When previously mentioned amounts of processed metals are considered, the robotized solution increases the amount of non-aluminum metals by approximately 15 kg per shift, amounting to 660 kg per month. Applying the average price of the non-aluminum metals of 3.5 EUR/kg brings a direct economic benefit of 2.300 EUR/month, only from the value of additionally extracted higher value metals. However, the related improved purity of aluminum from the current 88%–93% to at least 95% yields an additional 3.700 EUR/month. Consequently, the combined added value from improved sorting accounts for approximately 72.000 EUR/year.

The environmental impact of the increased metal purity is directly linked to reductions in energy consumption during the melting and purification process. It leads to lower emissions of sulfur dioxide, nitrogen oxides, and other hazardous substances as well as reduced waste generation of slag, dust, and other waste materials. Managing and disposing of these types of waste can be costly and environmentally challenging. Most importantly, since metals are finite resources, improved extraction during recycling leads to a reduction in the need for virgin material extraction and preservation of ecosystems. Using recycled metals with lower impurities in manufacturing processes can also lead to energy savings downstream, as materials with higher purities have better properties. This is especially true for copper with high electrical conductivity, where high-quality copper ensures that products which use it have better efficiency, and reduced energy consumption during their operational lifespan.

The introduction of robotized solutions enables management or maintenance workers to use the data from the camera vision system for statistical and real-time analysis of the shredding process, providing feedback. For instance, pieces that are shredded and are not the right size could indirectly mean that there are problems with the QZ device, which would require preventative maintenance. On the other hand, more non-metal pieces on the conveyor could mean that the Eddy current separation needs to be fine-tuned. The intelligent use of statistical analysis, combined with integration with other production entities, can lead to an optimized processing cycle in view of Industry 4.0 through connection with ERP systems, smart logistics scheduling, and reduced energy consumption. Using smart analysis of the sorting data opens a possibility for future live feedback to the Eddy current separator and QZ machine, which can be used for online tuning of the parameters to achieve better overall performance based on the historical and current size and composition of the parts on the non-ferrous metal sorting conveyor.

From a worker's perspective, the proposed solution perfectly illustrates the replacement of human workers with robots in dull, dirty, and dangerous environments. Workplaces in the recycling industry are often underpaid and risky due to the safety and health aspects of the work and are therefore desirable for automation, regardless of the economic aspects of the investment. Given the 8 h shifts and the potential negative impact on workers' eyesight, musculoskeletal injuries, and disorders, particularly in standing positions, the proposed automation is highly desirable for the workers involved. The study proposes complete automation as the ideal scenario for robot integration, where a machine replaces all workers. This scenario allows for the reassignment of all workers from the previously low-value-added assignment to other workplaces within the company, which is already experiencing a labor shortage.

However, given the complexity of the task, which includes variations in the shape, size, and weight of the metal pieces for separation, even partial automation can result in significant improvements for both the workers and the company. Compared to the current situation, a scenario where a single worker manages pieces undetected by the vision system or not picked by the robot offers significant benefits in terms of efficiency, ergonomy, and consistency. Reducing the workload for the worker directly improves their ergonomy and wellbeing by reducing stress and effort. In this scenario, the increased efficiency of the separation process, resulting from the reduction in workers assigned to the task and the near-perfect separation of non-ferrous metals, can directly and positively impact the remaining worker's wages, as it adds more value than before.

Regardless of the implemented scenario, both full and partial supervised automation yield direct economic benefit for the company in terms of a reduced number of workers engaged in the sorting task. With two shifts per day with four workers in each, even a partial automation scenario directly saves the company six salaries, giving the company a high incentive to apply it in the production. In this particular case, this yields a minimum saving of 36.000 EUR per year, when minimum wage in Serbia is considered for the calculation [64]. Together with added revenue related to the shredded aluminum purity and more efficient extraction of more valuable metals, the combined additional annual income/savings is comparable to the total cost of the robotized solution, indicating a very favorable return on investment.

The overall impact of the proposed solution can therefore be observed from different, but related, perspectives. The increased efficiency and quality of sorting leads to a higher purity of recycled non-ferrous metals, with direct and measurable economic benefits and incentives for its introduction. The environmental impact of the solution enables a reduction in carbon footprint related to processing of recycled materials. It increases efficiency, reduces energy consumption and waste disposal requirements, and lowers emissions and the reliance on virgin metal extraction, enabling natural habitat preservation. Advanced functionalities and integration with other production entities enable indirect benefits through processing optimization, enabling preventive maintenance and production traceability. Most importantly, the proposed solution does all the mentioned functions while improving worker's wellbeing, enabling the better working conditions needed for health preservation as well as reallocation to higher value-added positions.

## 6. Conclusions

Based on the facts presented in this paper, and in accordance with the research objectives, the following can be concluded:

- Most often, automated processes or vision techniques and collaborative robots assist humans in disassembling electrical devices during recycling. There are not many examples that demonstrate the separation of shredded parts from e-waste. As it is not possible to create a universal e-waste recycling system due to the variety of types and forms of e-waste, the application of partial automation in the form of a flexible e-waste sorting station that would combine computer vision and collaborative robotic systems has great potential in recycling. This would make it possible to take advantage of artificial intelligence, robotic systems, and the cognitive abilities of experienced workers that cannot be transferred to a robotic system, while the flexibility of the cell would be reflected in being easily adaptable for the separation of different types of e-waste that is recycled.
- The existing practice of e-waste management in Serbia is at a modest level, and the collection of this waste is performed only sporadically through organized periodic collection actions by recyclers. We have not even come close to achieving the established national goals in terms of the e-waste recycling rate. The reason for this state of affairs is the inconsistency of domestic legislation with the European one, the lack of the necessary infrastructure for e-waste management at the local community and state level, as well as the insufficient environmental awareness of Serbian citizens.
- The possible use of robots in the e-waste separation process was looked at, using the recycling center "E-Reciklaža" as an example. The analysis was grounded on real requirements and data from production, based on which a potential robotized solution was proposed and discussed in terms of implementation and the benefits it would bring. It was concluded that using robots in recycling would greatly improve workplaces that currently rely on manual labor and require workers to stand in awkward positions or deal with potentially hazardous materials like trash. The increased efficiency would have positive effects on wages, while the reduced workload would benefit the workers from sociological, ergonomic, and health perspectives. Moreover, it was shown that the increased sorting performance and quality would bring significant economic benefit to the company, making it a sound investment which would also have a profoundly positive environmental impact. The introduction of robotics would be a significant contributor towards strengthening of the local recycling ecosystem and would therefore have a positive impact on increasing Serbia's recycling rate.
- An insight into the gaps of the e-waste management system in Serbia with the proposal of potential solutions can help other countries in the region and beyond that face the same obstacles.

The constraints of this paper are limited data on e-waste management availability. Statistics on e-waste quantities, recycling rates and technologies may be incomplete or inaccurate. A significant part of e-waste is processed in the informal sector in Serbia, which can lead to unrealistic statistical data. A recommendation for future research of e-waste management in Serbia is to involve inter-country comparative analysis, which would be very useful. It would be especially valuable if the comparison were to be made with countries that have an organized waste management system, with a zero-waste approach, for example Sweden or Germany. This would give good guidelines for improving the e-waste management system in Serbia.

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