

Article

WEEE Recycling and Circular Economy Assisted by Collaborative Robots [†]

Esther Álvarez-de-los-Mozos ^{1,*}, Arantxa Rentería-Bilbao ² and Fernando Díaz-Martín ¹

¹ Department of Mechanics, Design and Industrial Management, University of Deusto, Avda. Universidades 24, 48007 Bilbao, Spain; fernando.diaz@deusto.es

² Tecnalia, Basque Research and Technology Alliance, Parque Tecnológico, 700, 48160 Derio, Spain; arantxa.renteria@tecnalia.com

* Correspondence: esther.alvarez@deusto.es; Tel.: +34-94-413-90-00

[†] This paper is an extended version of paper published in 29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), Limerick, Ireland, 24–28 June 2019.

Received: 16 December 2019; Accepted: 8 July 2020; Published: 13 July 2020



Abstract: Considering the amount of waste of electrical and electronic equipment (WEEE) generated each year at an increasing rate, it is of crucial importance to develop circular economy solutions that prioritize reuse and recycling, as well as reducing the amount of waste that is disposed of at landfills. This paper analyses the evolution of the amount of WEEE collection and its recycling rate at the national and European levels. It also describes the regulatory framework and possible future government policy measures to foster a circular economy. Furthermore, it identifies the different parts and materials that can be recovered from the recycling process with a special emphasis on plastics. Finally, it describes a recycling line that has been designed for the dismantling of computer cathodic ray tubes (CRT)s that combines an innovative participation of people and collaborative robots which has led to an effective and efficient material recovery solution. The key issue of this human–robot collaboration relies on only assigning tasks that require human skills to operators and sending all other tasks to robots. The first results from the model show a better economic performance than current manual processes, mainly regarding the higher degree of separation of recovered materials and plastic in particular, thus reaching higher revenues. This collaboration also brings considerable additional benefits for the environment, through a higher recovery rate in weight and for workers, who can make intelligent decisions in the factory and enjoy a safer working environment by avoiding the most dangerous tasks.

Keywords: human-robot collaboration; collaborative robots; WEEE waste management

1. Introduction

Waste of electrical and electronic equipment (WEEE) coming from household appliances, information technology and telecommunications equipment is rising all over the world at increasing rates. Some reasons accounting for this are fast technological changes, consumers' desire for the latest electronics products and difficulties to repair them. It should be noted that WEEE is one of the fastest waste streams. In 2016, an average e-waste of 16 kg/person was generated in the European Union (EU) [1] and the total amount in this area is projected to reach more than 12 million tons by 2020 [2].

As a result, landfill sites are filling up with WEEE, and a shortage of raw materials for these products is envisaged for the next years. On one hand, e-waste contains dangerous materials such as mercury, flame retardants, lead, chromium, barium, and cadmium, that must be separated and treated [3], which implies consumer awareness to return e-waste to separate collection points. Unfortunately, an important part of e-waste is still dumped illegally in poor countries and dismantled carelessly,

causing serious health problems and poisoning the soil, water and air. However, on the other hand, these products also contain valuable materials such as gold, copper, iron, aluminum. New circular economy models are a promising solution to tackle both issues since they can imitate natural ecosystems by taking advantage of cyclic processes in order to reuse and recycle as much as possible. The EU Circular Economy Package attempts to close the loop by complementing the measures contained in the legislative proposals and to contribute to meeting the United Nations Sustainable Development Goals adopted in 2015 [4]. Moreover, the recently launched European Green Deal [5] aims to “transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy, where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use”. As a matter of fact, one of its main elements is focused on “mobilizing industry for a clean and circular economy”.

Consequently, once end-of-life products are depolluted, valuable materials can be reintroduced in the market as secondary materials, thus extracting value from them and reducing the need for new materials. It must also be noted that moving to higher levels of the waste hierarchy in order to extend product lifetimes is not an easy task, due to consumer reticence towards second-hand items and difficulties in repairing end-of-life products.

The EU has put in place two directives to address the e-waste challenges: the Directive on waste electrical and electronic equipment (WEEE Directive) and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive). The main goals of this legislation are to improve waste management processes, eliminate hazardous substances, increase recycling capacity and introduce harmonizing legislation among the different European countries. In addition, these directives focus on producer responsibility to increase product recycling by making producers financially responsible for their products at the end of life. This aspect is very important because it is only through producers taking advantage of eco-design that the WEEE will achieve the goal of preventing so much electronic waste being generated [6]. Figure 1 shows the quantities of collected and treated WEEE.

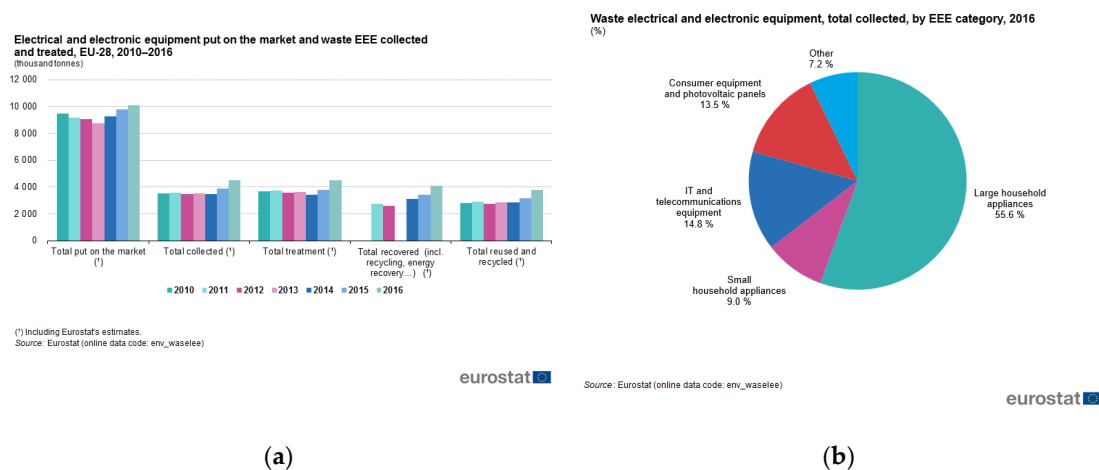


Figure 1. (a) EEE put on the market, collected waste and treated waste, EU-28, 2010–2016 [7]; (b) WEEE, total collected by EEE category, 2016 [7].

The first directive sets a collection target of 4 kg per inhabitant of WEEE from private households [8]. The EU 28 countries have complied with the collection rate target with 8.02 kg/capita collected for WEEE from households in 2017 [9]. In Spain, with a collection rate of 5.63 kg per inhabitant in that year and an increasing trend, the target has also been reached [9]. From 2018, the Directive was extended from a restricted scope to all categories of EEE, yet the gap between current results and future collection targets is very significant. Regarding IT and telecommunications equipment, the Directive sets a 75% recovery and 65% reuse and recycling target, which has been achieved in Spain. However, with the exception just a few members, reuse and preparation for reuse are not well developed at the EU

level [10]. Furthermore, some authors have argued that the absence of targets for the reuse of whole appliances and a lack of clear emphasis of reuse in national implementation of the European legislation undermine opportunities to promote reuse; therefore, recycling is the standard method for processing e-waste products [4].

Plastic is a very common manufacturing component because it is cheap and offers remarkable properties such as lightness, robustness, easiness to be shaped into many different forms and permeability to liquids. However, it has a big environmental impact. Plastic will only decompose over hundreds of years, fragmented into small pieces known as macro and microplastics, which end up in landfills, incineration plants or oceans. Microplastics have been detected in all oceans, including in deep-sea sediments and even in Arctic sea ice [11], constituting 75% of marine litter and posing a major threat to biodiversity.

Current recycling rates of plastics are very low, representing about 14% at the global level and 30% in the European Union [12]. On the contrary, landfilling and incineration rates of plastic waste in the EU remain high—31% and 39%, respectively. In the case of WEEE waste stream, landfilling accounts for 13% and incineration rate 44% [12]. Moreover, the annual growth of plastic waste of WEEE origin is 2.5%. The European Commission has established a share of 50% for WEEE plastics recycling target (Directive 2012/19/EU) by 2030. Plastic production in electrical and electronics sector in Europe represent a 6% and plastic waste generated by this sector accounts for 8% [13]. At the same time, demand for recycled plastics provides 6% of plastics demand in Europe.

According to [11], the major polymer types used are low density polyethylene (LDPE/LLPDE), polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), high impact polystyrene (HIPS), styrene-butadiene plastic (SB), acrylonitrile butadiene styrene (ABS), poly(propylene oxide) (PPO) and polyphthalamide (PPA), with polyethylene terephthalate (PET) and polyethylene's high density (HDPE) types being the most widely recycled, as well as PVC and PP being the most widely demanded [14].

In addition, several chemical additives are used at the manufacturing stage to improve polymer performance which are difficult to trace and can create obstacles to recycling. The presence of flame retardants (FR) impedes recyclability because current sensors cannot identify them. Bromine-based FR are classified as hazardous by EU Directives, and they must be separated. As a result, incineration is the preferred treatment for plastics containing FR.

There are methods which have managed to recycle blends of plastics like PC/ABS, coming from back covers, manufacturing new back covers which have passed all the materials testing (mechanical testing and presence of a maximum of hazardous materials, such as lead, mercury, cadmium, chromium and bromine) [14]. The production of recycled plastic is not yet economically competitive, and further investigation is needed in order to increase the efficiency of separation. Nevertheless, it is expected that G7 governments will support the market for recycled plastic by public interventions such as taxes for the use of virgin plastics or differentiated value added taxes for recycled plastics. As a matter of fact, the EU calls on the member states to promote economic instruments to prioritize waste prevention and recycling. One possibility is to consider introducing a modulated value-added tax (VAT) for products containing recycled content, so consumers will be incentivized to participate in this transition. In addition, internalizing the environmental costs of landfilling and incineration through higher fees or taxes could improve the economics of plastics recycling [13]. Additionally, due to the current scarcity of certain metals and other raw materials (cobalt, gallium, germanium, indium, platinum and related group, rare earths and tantalum), the European Commission has stated the importance of the recovery of such materials from waste products [15]. Considering the different types of materials, employees need to participate in identifying valuable materials by hand despite the existence of automated sorting facilities. The option of shredding whole devices implies losses of valuable materials (in particular, metals), which cannot be recovered in further sorting or refining processes. Therefore, optimized and selective disassembly of the devices is required to remove components containing important raw materials [16]. Recently, a method to transform plastic into an ultra-low sulfur fuel and other alternative

products to be used as fuel was developed by the Nantek company, by means of nanomaterials and thermochemical process, with promising results [17].

This paper identifies the different parts and materials that can be recovered from the recycling process of end-of-life computers. It also describes a recycling line that has been simulated for the dismantling of computer CRTs that combines the participation of people and robots which has led to an effective and efficient material recovery solution. The first results from the simulation model show a similar or even slightly better economic performance than current manual processes. Moreover, workers can enjoy a safer working environment by avoiding most dangerous tasks and make intelligent decisions to allocate tasks to either humans or robots.

2. Materials and Methods

The simulation model of a recycling line is based on the current manual solution that is being applied at an important company called Indumetal Recycling S.A., which is specialized in the integrated management of WEEE. One of its main waste streams comes from cathode ray tubes (CRTs). Even though CRTs are no longer produced, it is expected that CRT waste stream will still exist for about 10–15 years, with an estimated value of 2,400,000 tons of CRTs available in households and companies in 2020 [13]. This company applies the European Electronics Recyclers Association (EERA) options for treatment is shown in Figure 2 [18].

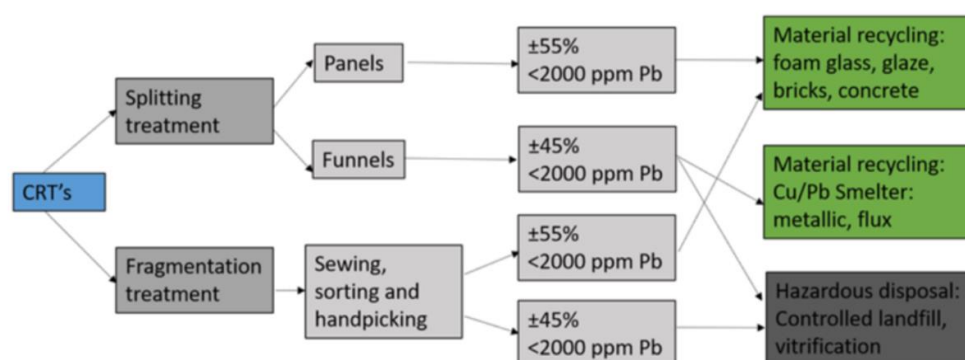


Figure 2. Current schema of treatment for cathode ray tubes (CRTs) (adapted from EERA schema) [18].

Table 1 shows the data related to CRTs collected by this company in kg in the period of 2015 to 2019. They treat as many CRTs as possible according to their capacity, else they store the remaining ones for future periods. Average total weight of the TV devices they receive (with CRT) is 15 kg/device, of which 88% (in weight) of the device is recycled [19].

Table 1. CRTs collected over time.

Number of CRTs	2015	2016	2017	2018	2019
CRTs collected (kg)	1,699,000	2,129,000	1,805,000	1,870,000	1,273,727

In relation to the fraction manually recovered after treatment of the TV set in the company expressed in percentage, average data are shown in Table 2.

The plastic fraction contained on a CRT can be divided in different types: PS (43% blended, 15% pure), HIPS (19% blended, 8% pure), SB (7%, blended, 2% pure), ABS (4%, blended), PPO/PS (2%), PP (1%, blended) [20]. Some additives are also present (often hazardous substances), such as flame retardants (FR) and stabilizers, which may change the material properties (melting point, flammability, density, etc.), and also reduce the recyclability [21].

Table 2. Material fractions recovered after treatment.

Fraction Recovered after Treatment	%
Metallic fraction	23.85
Plastic fraction	16.00
Glass fraction	57.60
Wood fraction	1.50
Condenser	0.06
Others	0.98
Fluorescent Screen Coat	0.01
TOTAL	100

When recycling CRTs, main problems are related to the identification of the type of polymer present (due to the lack of identification signs), and the mixture of different kinds of plastics (and plastic blended with metal) in a single type of equipment. The label which shows the type of plastic is present in only the 25% of CRT monitors; this figure rises to 58% for CRTs from TV sets [22], so the identification must be made manually or with some kind of technology based on sensors, such as near infrared devices (NIR).

Differences in end-of-life electronic devices give rise to difficulties in classifying and dismantling, which makes the recycling process impossible to automate. However, a fully manual process faces the problem of its high cost. A semi-automated process seems to be the most adequate solution because the process can be adapted to the condition of the electronic equipment, thus enhancing flexibility. The use of collaborative robots is related to industrial robots which work alongside human workers in the same workspace to jointly perform the assigned tasks [23,24]. This human–robot collaboration has gained a lot of interest, but real applications in industry are still scarce. By using collaborative robots, dull and dangerous tasks can be assigned to machines, leaving more interesting activities to humans. Therefore, accidents at the shop floor can be reduced, productivity can be increased, and higher job satisfaction can be reached by human workers. Many aspects related to human–robot interaction and collaboration remain challenging (safety, legal issues, liabilities), and this is a key issue to be addressed in order to provide robotic assistance to humans in many practical scenarios, such as assembling and disassembling [25]. The realization of such transfer operation indeed requires the robotic agent to be able to synthesize actions that are appropriate in terms of timing, kinematics, etc.

For robots to be effective in helping and collaborating with people in physical tasks, they must be capable of using robotic arms and hands to engage in fluent object exchange in real task settings. Just as for robots we use today in our manufacturing systems, the collaborative robots for disassembly will need to be able to manipulate and move physical objects (parts and tools) in the world, but this time in collaboration with people. This also implies the development of specific tools for disassembly (see Figure 3), systems to change tools when required (depending on the nature of the task), and specific sensory systems able to adapt the behavior of the robot to the characteristics of the device to be dismantled [26].

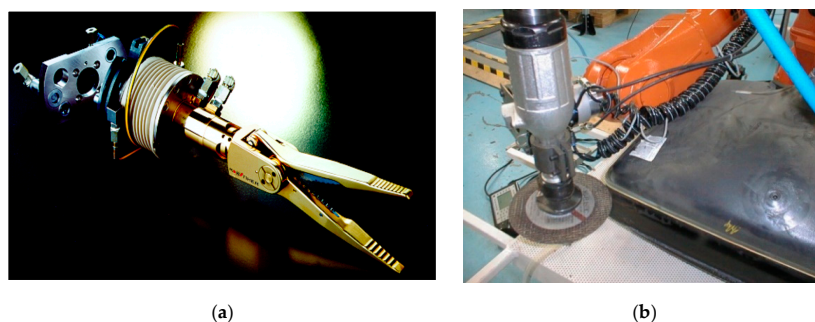


Figure 3. Specific tools for disassembly. (a) Pneumatic cutting tool with shock absorber; (b) Electric cutting saw.

The development of the sensing capabilities to guide the robotic decisions is also a challenge. One of the mostly widespread human–robot interaction frameworks is intuitive, where a robot can be instructed by an operator at the shop floor by natural means, such as gestures and speech [27,28]. The robot requires some information on the operation in order to optimize the interaction with the worker and the consideration of unplanned situations. Sensors such as machine vision-based systems provide information on the object to be manipulated during disassembling and recycling, and to estimate the human arm motion during the interaction [29]. In addition, by checking the barcode of the TV sets, the product model can be identified and, to certain extent, the types of plastic blend used in the back cover (the largest part of plastic present on a TV set) could be identified [30].

In order to provide the location of the human hand and, therefore, achieve the physical interaction with the robot, tracking algorithms have been developed, based on the robot operating system (ROS) and the Kinect X360, including tests for the detection and the monitoring of the human body posture. The recognition of the worker's hand and different components inside the device applies algorithms and descriptors using the point cloud library (point clouds with X, Y, Z coordinate system as result of a 3D scanning process), which includes a framework containing numerous state-of-the-art algorithms for 3D image processing, and the Microsoft Kinect sensor as a hardware platform. The objects of interest within the workspace perceived by the collaborative robot (worker's hand, objects) are found using segmentation and clustering techniques and identified by means of descriptors classification. The aim of this filtering is to improve and remove noise from the Kinect data for the recognition. The segmentation and clustering process to find the objects in the scene consists of a planar segmentation to remove the main plane from the scene and an Euclidean clustering process to obtain the interesting objects from the rest of the point cloud (specific algorithms are applied to extract the human hand, based on region flowing). The final part of the recognition process performs the classification process over a set of partial views of the models.

The safety of a robot–human collaboration has been analyzed and tested by TecNALIA in the European project COGLABORATION [31], through the use of vision systems, a fundamental component in robotic interactive systems. In the developed testbench, the safety of the human relies on the use of a Kinect XBOX 360, a real time controller and the intrinsic properties of the Kuka Lightweight Robot arm (LWR), specifically designed for interaction with humans (Figure 4a). The robot is able to detect potential collisions and stop its movement during the interaction with the operator thanks to the force feedback provided by the robot's architecture.

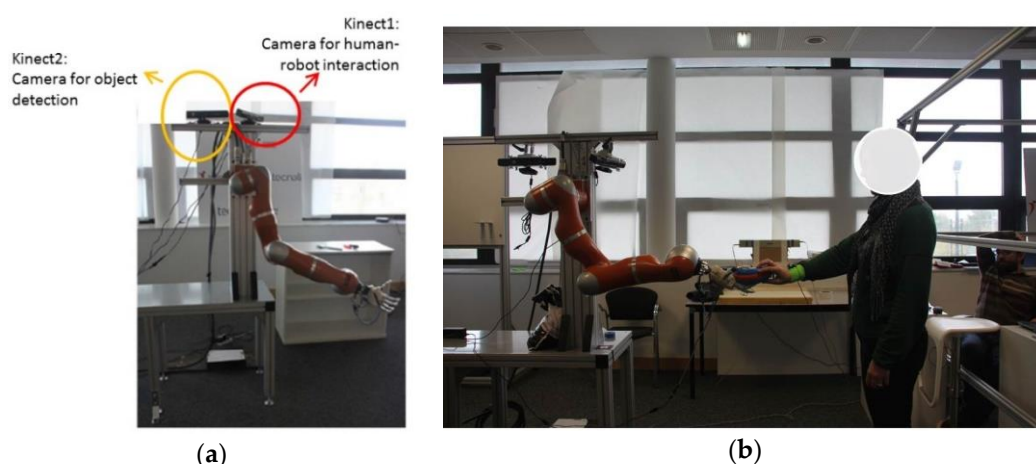


Figure 4. (a) Kuka Lightweight Robot (LWR) arm provided with cameras; (b) object exchange between robot and human.

In order to monitor the safety of the process, COGLABORATION also developed human detection techniques to adapt them to the object-exchange scenario. They ensure human safety in the robot workspace, where a human pre-collision detection and force threshold for post-collision detection were

implemented. Different information sources were used (e.g., mechanical contact by force sensors and computer vision), improving by this way the redundancy and robustness of the system. Additionally, procedures for object exchange and the detection of hand positioning and gestures were developed: hand and head location were localized using color-skin detection techniques in order to retrieve/plan the hand location for object exchange (Figure 4b).

3. Results

Proposal of a Disassembly Process Using Collaborative Robots

The human–robot collaboration has shown an evolution not only regarding technical features, but also the correct allocation of tasks. For assembly processes, the decision of introducing a robot for automation is based on both qualitative and cycle time-based criteria because the main objective is to complete a product in an effective and efficient way and on time. However, in the world of recycling, priorities are different: there is no due date, the arrival of disposed devices is difficult to forecast, and the components are not easy to recognize. The aim of an electronics recycler is to maximize revenues coming from the sale of the materials recovered and to maximize the space available in an area where waste is received and stored (part of the income comes from receiving shipments). Consequently, there is a lack of automation in the recycling process, adapted to the achievement of economical profit for the recycling company.

Several theoretical solutions for a completely automated process have been proposed, but only tested at the laboratory level. There is a need to improve the profitability of the recycling plants, by means of a selective configuration of operations to optimize the recovery and reuse of the obtained materials. At this point is where collaborative robots can play an important role, relying on the human factor in the task of recognizing the several types of components inside the device to be dismantled.

The efficiency of human–robot collaboration relies on assigning to operators only those tasks that require human skills, while assigning to robots all tasks that can be automated. Optimized distribution of tasks following this principle is the key to ensuring effective and efficient material recovery strategies.

The work of collaborative robotics can be based on observation, with goals inferred from the action of the operator (via machine vision and other sensing), combined with contextual cues and shared task knowledge to infer what actions the robot might take to complement the actions of the operator. Computers and televisions contain toxic substances which must be identified, as well as valuable and reusable materials. Glass represents the largest proportion of material in television sets and monitors, also being the main component of the cathode ray tubes (CRTs). In certain types of CRTs, it is necessary to separate the panel and funnel parts of the CRT, since they are reused in different ways due to their content of lead and other components. The second group of components comprises metal fractions (e.g., iron, aluminum, copper, and other precious metals), the foundry being their most common destination. Non-ferrous metals such as lead, zinc, and tin are also obtained. Plastics (mostly hazardous halogenated plastics used as flame retardants) are dangerous components because, if not treated, they become microplastics and enter the food chain of humans. Minor components include rubber, silicone, and sometimes wood. Figure 5 shows the flow of the transformation processes, transportation operations, control checkpoints and final stocks.

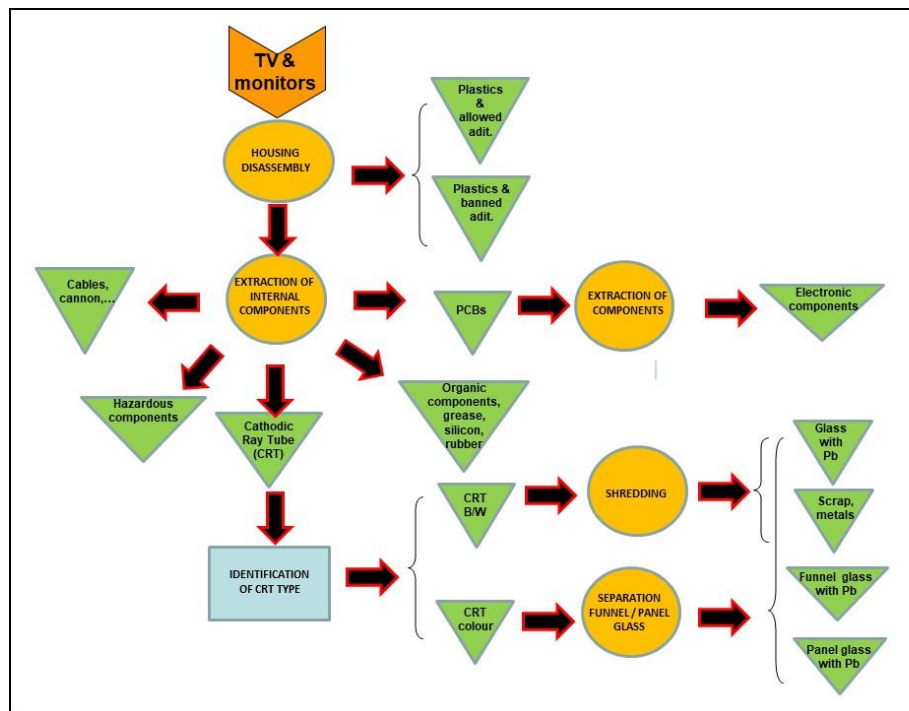


Figure 5. Flow diagram of the disassembly process.

An automated cell with collaborative robots, conveyors, disassembly stations, containers, etc. for the dismantling process of a TV set is proposed. The operations are as follows: a conveyor belt is used to bring TV sets into this cell (see Figure 6a). The presence of lead in the panel glass is resolved by a vision-based system, determining the further treatment of the CRT. If the panel is lead-free, the CRT must be separated into two parts—funnel and panel—otherwise, it can be shredded without previous separation (see Figure 6b). The collaborative robot should be able to learn the task from the operator, who shows the robot where to cut a cable or fixing, unscrew or manipulate a component, and where to discard it (by using his hands or gestures). In order to instruct the robot with certain parameters, additional spoken instructions can be provided. Therefore, the robot will be able to recognize commands such as “stop”, “go ahead”, “go to this point”, etc. For special cases where the reference points or sections are inside the electronic device, and where the visual clues are not clear enough for the robot, there is also the possibility of the operator taking the robot arm (in a passive mode) and leading it to these points to teach the tasks.

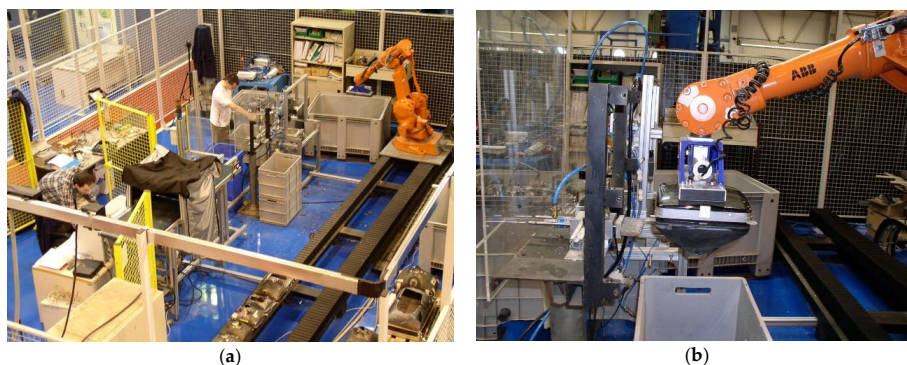


Figure 6. (a) Recycling line with robots and human operators; (b) robot performing dangerous tasks.

Advanced cutting-edge sensory, cognitive and reasoning abilities will allow the robot to execute the disassembly task in close co-operation with the human worker. Visual tracking of the worker

is required, directing attention to the relative positioning of the electronic device, its components, and the worker's body, arms and fingers. The robot uses a vacuum gripper to handle the CRT and transport it to the next workstations, where a rotating saw cuts the CRT along the joining line between panel and funnel. The funnel glass and other mixed parts (metal, silicone) fall into a container. Then, a robot moves to the next station, only with the panel part and the metallic band. A similar operation is carried out, where the metallic fraction falls in a container, and the robot takes the remains (panel glass) to a third container. Glass fragments are cleaned as a final operation. With the close cooperation between human workers and collaborative robots, higher degrees of plastic identification, separation and sorting can be achieved, resulting in an increased economic value of the recovered materials.

The shortening product lifecycles [30,32] and the increasing concerns regarding the sustainability of the current disassembling processes impose a higher degree of flexibility. In addition, the ageing of the workforce in industrialized countries [33,34] is of particular importance, resulting in a new role for the human operator in the recycling facility, from machine operator to flexible problem solver and commanding collaborative robots for specific tasks.

The process capacity of the detailed disassembly tasks applying collaborative robots is shown in Figure 7, which results in a productivity of 48 units/hour (compared to 30 units/hour when manual disassembling was used). Some tasks run in parallel, such as transportation tasks and activities regarding handling and disassembling. The process cycle time is about 1.25 min, with an average of EUR 2.57 treatment cost per unit.

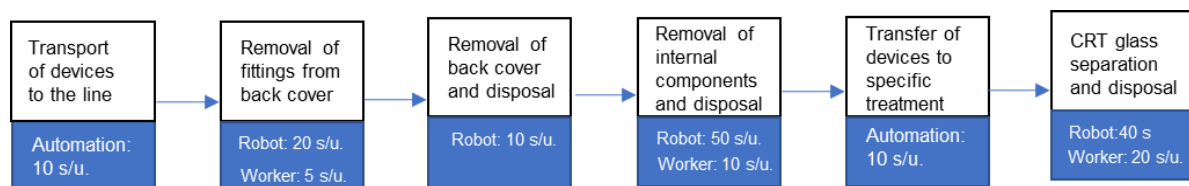


Figure 7. Flowchart of the disassembly process.

Further economic analysis has assessed the obtained results, covering the requested investments and revenues of the developed system, following traditional capital budgeting methods as well as new and complementary analysis based on the flexible equipment used in the recycling process. The applied indicators included the well-known parameters such as net present value, internal rate of return and pay-back period. In addition, an additional capital budgeting technique called capital-back, which takes into account the benefits of the flexibility of the proposed solution, has also been computed [35]. These indicators attempt to evaluate a single economic objective associated with the investment in advanced automated technology. Values obtained from these four indicators (Tables 3–5) show that the proposed solution for the dismantling plant was profitable.

Table 3. Recovered material (in a device with an average weight of 15 kg.).

Material	Quantity	Unit	Sale Price (€/t)
Copper	0.441	kg	5.771
Iron/Steel	1.620	kg	280
Aluminum and other metals	1.080	kg	1.690
PVC	0.700	kg	1.290
Funnel glass	2.430	kg	30
Screen glass	5.130	kg	30
Condensers	0.008	kg	240
Plastics for mechanical recycling	1.000	kg	717
Plastics for concrete manufacturers	0.666	kg	25
Polypropylene (plastics)	0.250	kg	400
Others	0.211	kg	0
TOTAL	13.54	kg	
Percentage of recovery (in weight)		90.24%	

Table 4. Main parameters for economic analysis.

Parameter	Quantity	Units
Productivity		
Number of TV/monitors processed	48	devices/h
Capacity of the recycling line	76,800	CRT/year
Total weight of the separated and recovered material	13.54	kg/unit
Percentage of recovery (in weight)	90.24	%
Revenues and operating costs		
Sales revenue	6.79	€/unit
Required workforce	6	workers
Number of shifts	1	shifts
Hourly workforce cost	15	€/h
Required investment	258,056	€
Annual operating expenses	146,080	€
Annual revenue from obtained material	521,187	€
Average treatment cost	2.57	€/unit

Table 5. Results of main financial indicators (5 years of lifespan, 5.5% discount rate).

Indicator	Value	Unit
Net Present Value	1,677,970	€
Internal Rate of Return	15,311	%
Pay-Back Period	0.69	years
Capital-Back	0.72	years

4. Discussion

In this paper, we have described an example of human–robot collaboration, where the allocation of tasks to either a robot or a worker is decided in real time by the latter depending on the condition of the discarded electronic device. Human operators play a leading role in the recycling process by deciding who will perform each task. Furthermore, they concentrate on tasks requiring human skills and flexibility. The role played by collaborative robots in the process is confined to that of performing dangerous and repetitive operations for human operators. Therefore, they complement the workers' role by making tasks safer and more productive.

A disassembly line has been described in which a close cooperation between humans and robots has achieved a more accurate identification of the different types of plastic encountered in CRTs, alongside higher degrees of plastic separation, resulting in more environmentally friendly solutions and an increased economic value of the recovered materials. Capital budgeting techniques have been applied to analyze the associated investment which indicate promising results, including a capital-back period of about nine months and an internal rate of return of 153%. Regarding the productivity of the line, the human–robot solution offers better results than the current manual solution and, more importantly, it is expected that the levels of job satisfaction and commitment will be enhanced. In this regard, it may be anticipated that operators will enjoy higher engagement values and improve both their performance and that of the organization as a whole [36]. In addition to that, by taking on more challenging tasks and performing valuable contributions, operators will be able to enjoy work meaning and enrichment at a human level [37]. One of the aspects that will change in the future work scenario would be a better trained staff alongside the presence of more women at work. These changes have proven to have positive effects on productivity and economic growth [38]. In addition, the increasing number of elderly people at work is a reality. These facts make the introduction of collaborative robots a key factor to improve the working conditions. This holds true with respect to the physical point of view when the task is demanding (such as disassembly activities) and it is performed by elderly or women workers, but also with respect to the psychological effect for general workers, who ask for a higher participation in taking control and making decisions over their work.

Work characteristics not related to wage, such as autonomy, trust and stress, are important for the satisfaction of workers and, therefore, for job retention [39]. The introduction of robots and related technologies (information and communication technologies, artificial intelligence) increase job satisfaction [40]. However, these new tools may also imply higher levels of stress. Compared to manual tasks (now carried out by robots), the problem-solving and more complex tasks performed by humans bring more mental loads. Therefore, it is important that the distribution of disassembly tasks (between humans and robots) and the learning capacities of the collaborative robots are adapted to the different requirements of the disassembly activities and the needs and preferences of the human workers. There are additional social implications, since some recycling companies often work as social enterprises, with many employees in the second labor market.

Further research is planned to use teleoperated robots to disassemble devices in dangerous environments where the operator must be positioned outside the area in which the disassembly operations are being carried out (e.g., in nuclear, chemical or bacteriological facilities).

Author Contributions: Conceptualization, E.Á.-d.-I.-M.; methodology, A.R.-B. and E.Á.-d.-I.-M.; writing—original draft preparation; writing—review and editing, E.Á.-d.-I.-M., F.D.-M.; investigation, resources; software, A.R.-B.; formal analysis and validation, F.D.-M.; supervision, E.Á.-d.-I.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We would like to acknowledge Indumetal Recycling for giving us access to their data.

Conflicts of Interest: The authors declare no conflict of interest.

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