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Human-Robot Collaboration as a new paradigm in circular economy for WEEE management

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Abstract

E-waste is a priority waste stream as identified by the European Commission due to fast technological changes and eagerness of consumers to acquire new products. The value chain of the Waste on Electric and Electronic Equipment (WEEE) has to face several challenges: the EU directives requesting collection targets for 2019–2022, the costs of disassembly processes which is highly dependent on the applied technology and type of discarded device, and the sale of the obtained components and/or raw materials, with market prices varying according to uncontrolled variables at world level. This paper presents a human-robot collaboration for a recycling process where tasks are opportunistically assigned to either a human-being or a robot depending on the condition of the discarded electronic device. This solution presents some important advantages; i.e. tedious and dangerous tasks are assigned to robots whereas more value-added tasks are allocated to humans, thus preserving jobs and increasing job satisfaction. Furthermore, first results from a prototype show greater productivity and profitable projected investment.

Keywords: Collaborative robots, e-waste, circular economy

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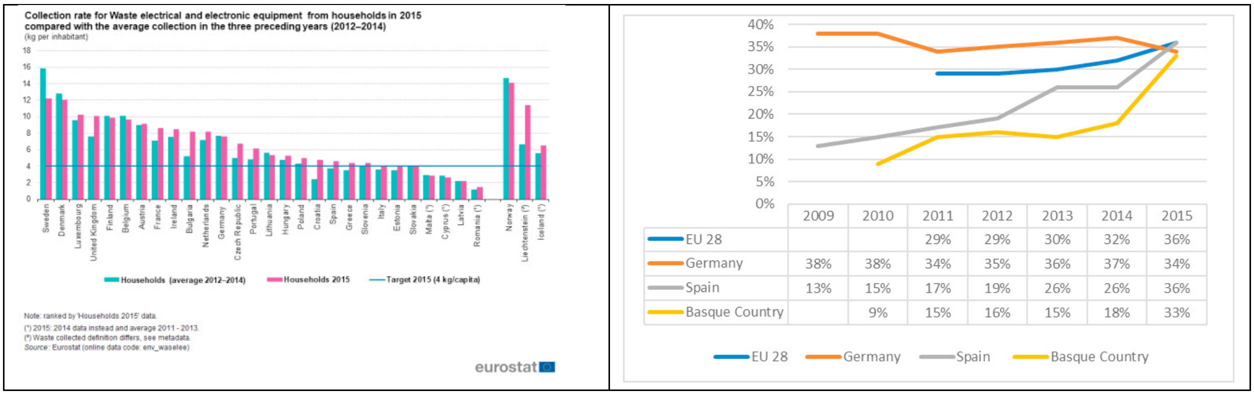
1. Introduction

Nowadays, our economy is subject to an increasing tension between production needs and limited landfill capacity to absorb waste of end-of-life products. In the case of waste of electrical and electronic equipment (WEEE) such as computers, cell phones, fridges or TV-sets this tension is even greater due to fast technological changes, difficulties to repair them and eagerness of consumers to acquire new products. In fact, WEEE is one of the fastest waste streams in the EU with 9 million tonnes generated in 2012 and is expected to grow to more than 12 million tonnes by 2020 [1].

But these products contain both valuable and hazardous materials inside that must be correctly separated at the end of their life-cycles. On the one hand, iron, aluminium, glass, plastic or copper and gold can be recovered. Some of these resources are scarce and expensive. On the other hand, dangerous materials such as lead, chromium, barium, cadmium, mercury, flame retardants must be separated and treated [2]. If hazardous content is not properly managed, it can cause serious environmental and health problems. These problems can be attenuated if the behaviour of natural ecosystems is imitated to take advantage of cyclic processes in order to reuse, remanufacture and recycle as much as possible. New circular business models have emerged as a result of the increasing request for a more sustainable use of resources. Therefore, once end-of-life products are decontaminated, valuable materials can be reintroduced in the market as secondary materials.

In order to handle these problems, the EU has put in place two directives: 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). 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 [3]. The first one sets a collection target of 4 Kg/capita and a 20 Kg/capita to be brought in 2019.



	2009	2010	2011	2012	2013	2014	2015
EU 28			29%	29%	30%	32%	36%
Germany	38%	38%	34%	35%	36%	37%	34%
Spain	13%	15%	17%	19%	26%	26%	36%
Basque Country		9%	15%	16%	15%	18%	33%

Fig.1. (a) Collection rate for WEEE from households in 2015 [4]; (b) WEEE recycling rate (%) [4] [5].

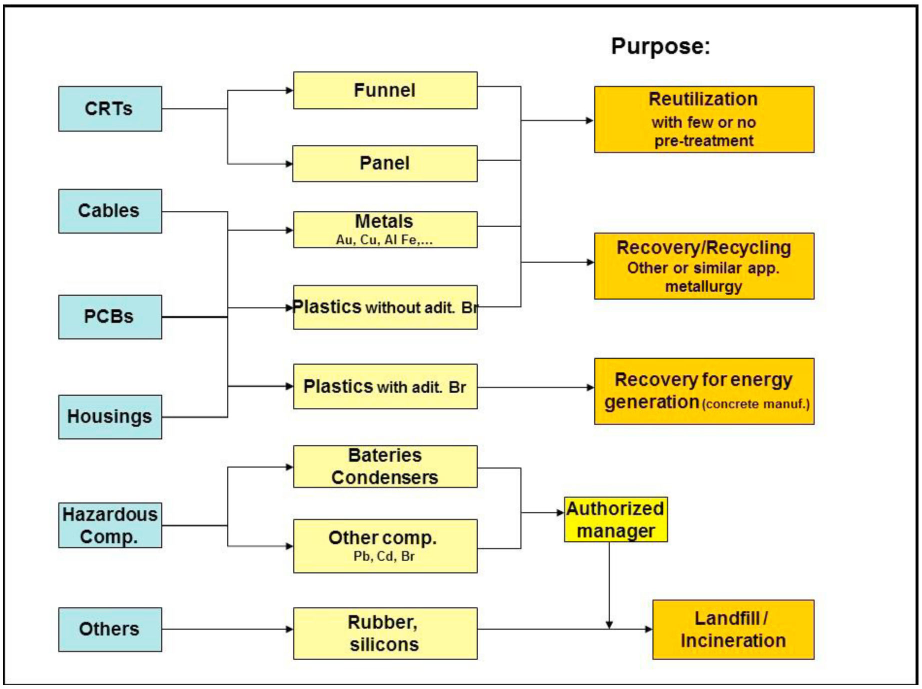
As can be seen in Fig. 1a, most EU countries have complied with the collection rate target of 4 kg/capita set for WEEE from households in 2015. In Spain, with a collection rate of 4.61 kg/capita in that year and an increasing trend, the target has also been reached. In addition, in the Basque Country the collection rate also exceeded the established minimum level with 6.01 kg/capita in the same year [6]. Although from 2018 the Directive will be extended from its current restricted scope to all categories of EEE, the gap between current results and future collection targets is very significant. In relation to the WEEE recycling rate shown in Fig. 1b, both the Basque Country and Spain experienced an important increase, the latter reaching the 36% average EU 28 level in 2015 [4]. Regarding IT and telecommunications equipment, the Directive sets a 75% recovery and 65% re-use and recycling target which has been achieved in Spain. But with the exception just a few Members, re-use and preparation for re-use are not well developed at the EU level [7].

2. Main disassembly tasks in WEEE

Indumetal Recycling S.A. is a Basque company which specializes in the integrated management of WEEE and complex scrap, including logistics services and the dismantling of industrial facilities. One of its main waste streams comes from Cathode Ray Tubes (CRT's). Although CRTs are no longer produced, and therefore no efforts on eco-design can be applied to them, the presence of CRT waste stream is still to be here for about 10-15 years, and in the year 2020 it is estimated that about 2,400,000 tonnes of CRT's will be available in households and companies [8].

The current schema of treatment for CRT's in this company follows the European Electronics Recyclers Association (EERA) options for treatment is the following:

Fig. 2. Current schema of treatment for CRT's (adapted from EERA schema)



The recycling process of electrical and electronic equipment faces some difficulties related to classifying and dismantling. The lack of uniformity of the discarded electronic devices makes the recycling process impossible to automate so they currently use a purely manual solution. Therefore, no predetermined process is applied to all devices, but it is adapted to the condition of the electronic equipment. Moreover, the data related to CRT's collected and treated in kg. in the period (2015-2017) is shown in table 1. No exact data were provided by the company for CRTs treated in 2015-2016 but it is assumed that they are similar in percentage to the ones available in 2017.

Table 1. CRTs collected and treated.

	2015	2016	2017
CRTs collected (kg)	1,699,000	2,129,000	1,805,000
CRTs treated (kg)			1,686,000

In relation to the fraction recovered after treatment in the company expressed in percentage, data are shown in table 2. Finally, the productivity of the production line is 30 units per hour.

Table 2. CRTs collected and treated.

Fraction recovered after treatment	Percentage
Metallic fraction	23.8 %
Plastic fraction	14.98%
Glass fraction	57.60%
Wood fraction	1.50%
Condenser	0.06%
Others	2.00%
Fluorescent Screen Coat	0.01%
TOTAL	**100%**

3. Collaborative robots: the new paradigm in robotic manufacturing and demanufacturing tasks

The use of collaborative robots also called Human-Robot Collaboration is related to industrial robots which work alongside human workers in the same workspace to jointly perform the assigned tasks [9]. This concept has gained a lot of interest in the scientific community, although real applications in industry are still scarce. Through collaborative robots dull and dangerous tasks can be assigned to robots leaving more interesting activities to humans. Therefore, accidents at the shop floor can be reduced, productivity increased, and higher job satisfaction can be offered to human workers. Many of the aspects related to human-robot interaction and collaboration remain challenging, even though this is a key aspect to be addressed in order to provide robotic assistance to humans in many practical scenarios. 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 in the world, but this time in collaboration and with people [10]. Another problem is the development of the sensing capabilities to guide the robotic decisions. 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 [11]. The interaction with the worker and the consideration of unplanned situations require providing the robot with some information on the operation. Machine vision-based information is a key sensor which provides information on the object to be manipulated during disassembling and recycling, and to estimate the human arm motion during the interaction [12]. Also, by checking the bar code of the electronic device the product model can be identified and, to a certain extent, the types of plastic blend used in the back cover (the largest plastic part), can be recognized [13].

Tracking algorithms have been developed to estimate the human position, 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 objective is to provide the location of the human hand, and therefore achieve the physical interaction with the operator. 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 using 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 get the interest 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.

4. Proposal of a disassembly line for WEEE integrating 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 possibility of introducing a robot for automation is based on both qualitative and cycle time-based criteria. This rationale is based on the fact that in a traditional manufacturing process, the main objective is to complete a product in an effective and efficient way and on time. But 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 available space in an area where waste is received and stored since part of the income comes from receiving shipments. As a result, there is a lack of automation in most recycling processes.

On the other hand, several solutions for a completely automated process have been proposed, but they are often theoretical developments at laboratory level. In addition, most proposed processes rely on geometric information of the appliances and apply simulation to plan the theoretical separation. 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 collaborative robots can play an important role, entrusting the human factor with the task of recognizing the several types of components inside the device to be dismantled. The efficiency of human-robot collaboration relies on assigning only tasks that require human skills to operators and those that can be automated to robot strategies. The work of collaborative robots can be based on observation, where robots infer what to do by interpreting operators' instructions (via machine vision and other sensing), combined with contextual cues and shared task knowledge, so that both resources complement each other.

Computers and televisions contain valuable and reusable materials and components. They may contain toxic substances which must be identified and separated. Glass represents the largest proportion of material, (25% in weight), in television sets and monitors, being the main component of the CRTs. Sometimes, it is necessary to separate the panel and funnel parts of the CRT, since they are reused in different ways due to their lead content and other materials. Metal fractions constitute the second group of components (iron, aluminum, copper, and other precious metals), having foundry as the most common destination. Among the non-ferrous metals, lead, zinc, and tin are obtained. Plastics are the third group. They may include hazardous components, mostly halogenated plastics used as flame retardants. Moreover, they pose a serious environmental problem because, if not treated, they become microplastics and enter the food chain of humans. Other components are rubber, silicone, and sometimes, wood.

We propose a semi-automated cell for dismantling TV sets which includes collaborative robots, conveyors, dismantling stations, containers, etc. The sequence of operations performed by the cell are as follows: a transportation belt is used to enter TV sets into this cell, then a vision-based system identifies the presence of lead in the panel glass, which determines 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 fig. 3a). The collaborative robot can learn the task from the operator. For example, he/she will show the robot where to cut a cable or fixing, unscrew or manipulate a component, and where to discard it. The human operator may use his/her hand and fingers to show specific reference points in the components, so the robot will use them to cut or take the part. Additional spoken instructions can be provided by the worker to instruct the robot with certain parameters. Therefore, the robot will be able to recognize hand gestures such as "stop", "go ahead", "go to this point", etc. In special cases in which the reference points or sections are inside the electronic device, or 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. Augmenting the robot with cutting-edge sensory and cognitive abilities as well as reasoning abilities will allow the execution of the disassembly task in close co-operation with the human worker. To reach this objective, visual tracking of the worker is required, directing attention to the relative positioning of the electronic device, its components, 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 (see fig. 3b). A similar operation is carried out, where metallic fraction falls in a container, and the robot carries the remains (panel glass) to a third container. The final operation of this process is the cleaning of the glass fragments. Higher degree of flexibility on disassembly processes will be required due to shorter product lifecycles, which implies new designs and new materials [14] [15]. Also increasing concerns regarding the sustainability of current disassembling processes, emphasize the need to rethink how these processes are carried out. Additionally, in industrialized countries the ageing of workforce is a key issue [16] [17], with a new role of the human operator in the recycling facility, from machine operator to flexible problem solver and commanding collaborative robots for specific tasks. The technical feasibility of the proposed process and task distribution between robot and human has been assessed using analytical simulation techniques. Specifically, the commercial software package Siemens PLM / Robcad has been used to simulate several configurations of the treatment plant (see fig. 3). The aim is to execute virtual operations of cells, detect potential failures in design, and optimize distribution of machines, conveyors, dismantling stations, containers, tools, workers and robots. Once the analysis is finished, the design is translated to the real world. The treatment cycle times and costs have been obtained from this simulation analysis, performed with several recycling line configurations.

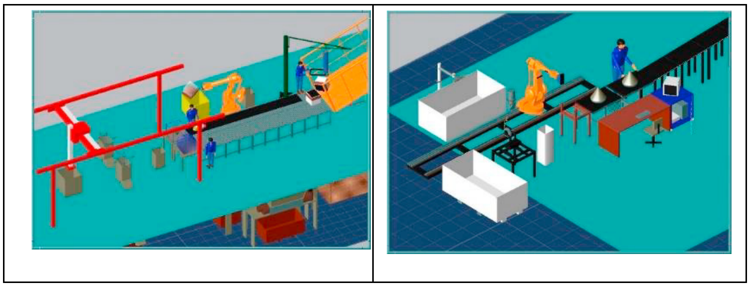


Fig.3. (a) Human-robot station; (b) CRT recycling.

5. Obtained results and economic analysis

The obtained results have been assessed by economic studies, covering the requested investments and revenues of the developed system, following well-known methods as well as new and complementary analysis based on the flexible equipment used in the recycling process. The economic studies included the widespread capital budgeting methods Net Present Value, Internal Rate of Return and Pay-Back Period which attempt to evaluate a single economic objective associated with the investment in advanced automated technology. Additionally, the Capital-Back, which bears in mind the flexibility of the automation components that constitute the recycling installation, has also been computed. Although economic values obtained from these methods for the proposed solution are slightly worse than those obtained by a full manual process, they are clearly positive, whereas productivity is higher.

Table 3. Sequence of disassembly operations and cycle times (s.).

Task	Automation equipment	Robot	Worker
Entry of device to disassembly line	10		
Removal of fittings from back cover		20	5
Removal of back cover & disposal		10	
Removal of internal components & disposal		50	10
CRT is moved to specific treatment	10		
CRT glass separation & disposal		40	20

Table 4. Recovered material (in a device with an average weight of 17 kg)

Material	Quantity	Unit	Sale price (€/ t)
Copper	0,552	kg	5,771
Iron	1,179	kg	280
Aluminium	0,034	kg	1,690
PVC	0,204	kg	1,290
Funnel glass	2,200	kg	30
Screen glass	4,890	kg	30
Condensers	0,005	kg	240

Polipropilene (plastics)	0,504	kg	5,771
CRT silicone	1,350	kg	0
Percentage of recovery (in weight)	**78**	**%**	

Table 5. Estimation of investments for the proposed disassembly line.

Equipment for recycling line	Cost (€)
Feeder	13,440
Rolling transport system	6,720
Manipulator (hand controlled)	14,784
Table for disassembly, tools, extractor	6,720
Infrared detector	20,000
Computer	800
Conveyor system for back covers	3,360
Mill for recyclable plastics	56,000
Mill for other back covers	56,000
Surface cleaning system	672
Robot for back covers (incl. image analysis)	30,000
Robot for CRT (incl. image analysis)	30,000
Grippers & other tools for robots	5,000
Conveyor for CRTs	1,680
Control case and cabling	2,800
Safety components	1,120
PLC	1,120
Pneumatic actuators	1,120
Conveyor and discharging chute	6,720
TOTAL	**258,056**

Table 6. Main parameters for economic analysis

Parameter	With collaborative robots	Full manual	Units
Number of TV / monitors processed	32	30	Devices/ h
Capability of recycling line	102400	93667	CRT / year
Total weight of the separated and recovered material	13.52	Id.	kg / unit
Recycling percentage (in weight)	79	Id.	%
Income for material sales	4,5	Id.	€ / unit
Required labor	4	Id.	Worker
Number of shifts	2	Id.	Shift
Hour labour cost	15	Id.	€ / h
Required investment	258056	191936	€
Yearly exploitation costs	100160	Id	€
Yearly income for obtained material	461129	Id	€
Average treatment cost	1.5	1.5	€ / unit
Results of main financial indicators (5 years of lifespan, 15% discount rate):			
Net Present Value	1,180,000	1,376,867	€
Internal Rate of Return	147	213	%
Pay-Back Period	0.71	0.49	years
Capital-Back	0.88	0.81	years

6. Conclusions

In this paper we present a human-robot collaboration for a recycling process where tasks are allocated to either a human-being or a robot depending on the condition of the discarded electronic device. This solution presents some important advantages; on the one hand dangerous tasks are assigned to robots and more complex tasks are allocated to humans. On the other hand, flexibility is increased since no predetermined process is applied to all devices, but it is adapted to the condition of the device. To sum up, robots do not necessarily substitute human labor, but complement it and, in specific areas, make it even more productive. The automation of part of the work due to human-robot collaboration can improve the working efficiency. The human operator can focus only on the portion of work which requires human skill and flexibility, allowing for an adaptation to different types and conditions of the devices to be dismantled. It is expected that operators will also increase their engagement values and thus their operative results, maximizing their individual performance and therefore the organizational performance [18]. Moreover, job can gain work meaning by allowing operators to use their own judgement to make decisions through more challenging tasks and the possibility to make valuable contributions [19]. Therefore, these working conditions can reduce occupational illnesses and enrich job at a human level. An economic analysis of the proposed solution has also been presented. First results from a prototype show less time to complete the recycling process and greater productivity, as well as positive capital budgeting results. Future work includes the use of teleoperated robots to disassemble devices in dangerous environments (nuclear, chemical sites), where the operator must be located outside of the area where the dismantling is being performed.

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