Chapter 5
Highly Evolvable E-waste Recycling Technologies and Systems

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Abstract Materials recycling is a key process to close the loop of materials in the direction of circular economy. However, the variability of waste and the high volatility of the price of recovered materials are posing serious challenges to the current rigid design of mechanical recycling systems. This is particularly true for Waste Electric and Electronic Equipment (WEEE), whose volume is growing more than other waste streams in Europe due to the diffusion of electronic products and to their short technology cycles. This study is aimed at the development of new flexible recycling systems through the implementation of a Hyper Spectral Imaging system and a simulation model enabling the real-time characterisation of shredded particles and the dynamic optimisation of process parameters for efficient sorting. A hardware and software prototype was realised and tested at the De- and Re-manufacturing pilot plant of CNR-STIIMA. The positive economic impact of flexible recycling systems enabled by new technologies was assessed through scenario analysis.

5.1 Scientific and Industrial Motivations

De-manufacturing acquired high relevance in last few years due to increasing raw material costs and to laws in many countries aimed at improving material recycling rates and at limiting supply shortage risks for rare metals used in high-tech applications. While manufacturing transforms raw materials into products meeting the

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customer requirements, de-manufacturing transforms post-consumer products into valuable materials meeting the customer requirements for secondary use. However, manufacturing and de-manufacturing objectives are strictly dependent. In fact, products that are currently manufactured will constitute the waste that will be treated by de-manufacturing system in the next years.

De-manufacturing can be defined as the set of processes, technologies, tools and knowledge-based methods to re-use, re-manufacture and recycle materials and components from End-of-Life products [1]. The de-manufacturing process includes the following steps:

1. *Disassembly* that aims at separating (i) hazardous components that have to be treated separately, (ii) re-usable components with high residual value, (iii) components needing to go through a special recycling process due to their material composition. In general, in the current state of the art, most of disassembly operations are performed manually.
2. *Mechanical pre-treatment* that consists in shredding, reduction of particles' size and separation of different materials flow. The goal of separation stages is to split a mixed input material flow into two or more output flows that are characterised by a concentration of target materials higher than in the input flow. The size-reduction of the particles can help to isolate target material from other type of materials, thus increasing the quality of the downstream separation process.
3. *Material recovery or end-refining* by means of chemical and thermal processes separating target materials at very high grade levels to obtain compounds that can be re-used for the production of other materials.

According to recent studies, the major cause for losses of key metals (from 40 to 100% of material) in de-manufacturing process is the low efficiency of the mechanical pre-treatments step, while only marginal losses are due to the collection and to the downstream chemical end-processes. Therefore, the improvement of mechanical recycling technologies and systems is important for the recycling and high-tech product manufacturing sectors.

Currently, recyclers perform the mechanical pre-treatment of wastes, including metal and non-metal fraction, by:

- manual dismantling processes, to isolate hazardous components and easily disassemble parts;
- mechanical shredding and separation processes, aimed at reducing the size and refining the input material into purified material flows that can be sold either in the market (aluminium, copper, steel) or to end-processing plants for further purification (such in the case of Printed Circuit Boards).

In Europe, 85% of recycling companies are Small Medium Enterprises (SMEs). Due to the space and budget limitations, it is extensively challenging for these companies to operate dedicated treatment lines for mechanical shredding and separation processes for each specific product flow. Batch production and high utilization of a single or few recycling lines is a common solution. The process parameters are selected as a compromise between the different product types, thus leading to un-optimised performance. Moreover, in spite of the high variability of post-use products and material to be treated, currently available mechanical recycling systems are extremely rigid and they cannot be adapted to the different type of waste which is generated over time according to the technology cycle of products. Their design and technology does not allow to dynamically modify process parameters and material routing based on the specific type of mixture to be treated. In addition, the integration of new process technologies in the system is extremely time-consuming and expensive, since the rigid conveyor systems need to be re-arranged for the specific purpose with long ramp-up times. For these reasons, aligning recycling with the evolution of products and waste is a significant challenge. The system rigidity, coupled with the high variability in the input material composition and in the targeted output performance, ultimately causes many shortcomings of the process including:

- low recycling rates, especially for key-metals;
- excessive recourse to landfilling also for materials that could be potentially recycled, such as high value-added plastics;
- lack of competitiveness of the Small Medium Enterprises that typically apply mechanical recycling processes, and
- untapped market potentials for the recycling industry.

Thus, the development of flexible and adaptable systems for the recycling industry is a promising avenue for the improvement of material recovery and for the adoption of recycled material in high-quality and high-value applications [2, 3]. The concepts of flexibility, re-configurability and adaptability have already been widely investigated in the scope of manufacturing systems [4–7], but they have been poorly addressed until now in the de-manufacturing area. Grounding on a solid knowledge base derived from manufacturing industry and getting inspiration from changeability enablers adopted in manufacturing processes, research activities should aim at the development of innovative technologies for supporting the transition towards smarter de- and re-manufacturing systems characterized by: (i) high adaptability to different waste to be treated and to changing market conditions, (ii) high automation level, (iii) availability and traceability of information, and (iv) intelligent decision algorithms based on data analytics and cyber-physical systems.

To this aim, a set of *hardware and software systems as well as business model applications* are required to be integrated, enabling a feedforward control to manage the system evolution leading to a more coherent matching between the fast dynamics and large variability of the End-of-Life product life-cycle and the system life-cycle, also called *co-evolution* [8]. Co-evolution is defined as the ability of a company to address engineering change according to context modifications, strategically and operationally, in order to gain and maintain competitive advantage [8]. The change propagation acts as a cause-effect wave across the various company domains, spanning from corporate strategy to plants and technologies. The co-evolution problem has been traditionally studied within the manufacturing industry (e.g. within the

EU funded projects RobustPlanet,[1] RLW Navigator,[2] DEMAT[3]) but has never been addressed within the de-manufacturing sector.

This work investigates the implementation of the co-evolution principle for de-manufacturing systems. New flexible and adaptive recycling systems are proposed while addressing the process technology and ICT development. Furthermore, new business and financial models are developed to enable the industrial uptake and large-scale diffusion of the new processes by dynamically suggesting the best strategies to adopt and guaranteeing process and business dynamic adaptation to waste flows evolution over time.

The chapter is organised as follows. Section 5.2 presents the state of the art on flexible recycling systems. Section 5.3 outlines the research scope and approach, whereas Sect. 5.4 presents the different results of the research (i.e. hardware and software solutions, business model validation and prototypes). The results of industrial testing are discussed in Sect. 5.5 and, finally, the conclusions together with indications for future research are presented in Sect. 5.6.

5.2 State of the Art

The literature about recycling systems mainly concentrates on process planning [9] and economic assessment of the processes [10]. However, recent literature showed that in order to efficiently treat different material mixtures in the same mechanical material separation plant, the system itself should be designed to enable on-line modifications of the material flows [11]. Figure 5.1 shows how different routing configurations in the same system can bring to significantly different recovery and grade performance. In particular, treating multiple products would support coping with low revenues from material treatment, high variability of products and limited availability of specific post-use products, thus the capacity constraints [12, 13]. Therefore, the system architecture should be modified depending on what products are treated and which is the target recycling rate of the materials. If the system configuration and the process sequence is not modified when the mixture under processing changes, then the performance of the entire system drastically drops making the recovery process unsustainable for some products.

The volatility of material price and the high variability in composition of the input material represent considerable challenges for the sustainability of recycling systems due to their rigid designs. The major limitations in terms of flexibility of state of the art recycling technologies regard, among all, the two following aspects:

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[1] ROBUSTPLANET—“Shock—robust Design of Plants and their Supply Chain Networks”, FoF. NMP. 2013–9 Grant Agreement no 609087.

[2] FP7-2011-NMP-ICT-FoF EU Project, RLW Navigator “Remote Laser Welding System Navigator for Eco & Resilient Automotive Factories”, Grant Agreement no 285051.

[3] DEMAT—“Dematerialised Manufacturing Systems: A new way to design, build, use and sell European Machine Tools”, FP7. NMP. 2007–2013 Project ID 246020.

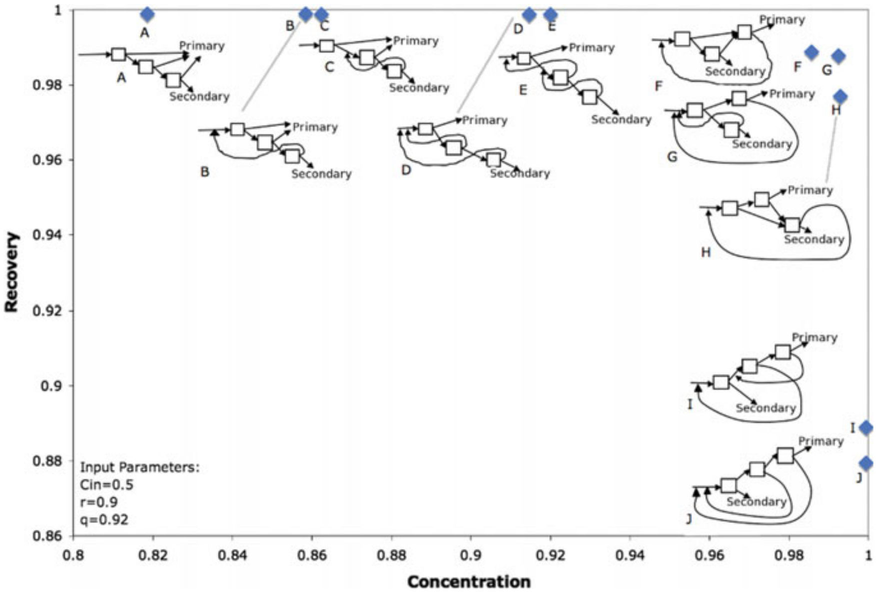

Fig. 5.1 Optimal system configurations as a function of recovery (y-axis) and grade (x-axis) targets [11]

- Modelling, control and optimisation of the recycling process.
- Low performance of hyperspectral imaging to identify metal and non-metallic materials.

Within the research on recycling process modelling and control, separation process modelling has attracted interest from researchers, especially in the mineral technology area [14]. Physical models for particle trajectories in Corona Electrostatic Separation (CES) have been developed [15]. However, these models are always focused on single particle trajectories and do not support the modelling of two relevant causes determining the low performance of separation process, i.e. (i) particle impacts and interactions, and (ii) the presence of unliberated particles in the material flow. Discrete granular material flow models could handle these issues. Very recently, multi-particle and multi-body simulation models have been developed to analyse the dynamics of the impacts within recycling processes (Fig. 5.2) [16]. Although these models outperform existing ones to explain the process physics, they are relatively time consuming tools and hard to be used to support process optimization and control. Moreover, their validation in real settings is still ongoing.

Regarding hyperspectral imaging for metal and non-metallic materials, current methods to distinguish and characterise the composition of parts and shredded particles are based on off-line inspection, colour inspection systems, X-Ray, X-Ray-Backscatter or even spectroscopy over thermally stressed materials [17]. However, these methods are inaccurate with chromatic materials (mainly metals) or their adop-

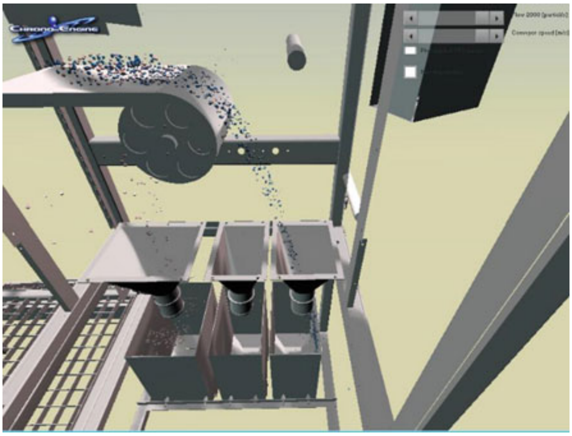

Fig. 5.2 Multi-particle CES simulation model

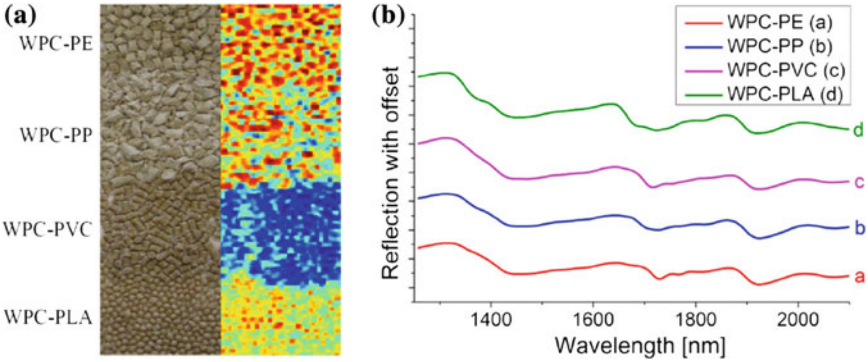

Fig. 5.3 Application of hyperspectral imaging for identification of plastics products: **a** classified images, **b** related reference spectra [22]

tion is not feasible in industry where on-line inspection procedure is becoming extremely important [18–20]. As a matter of fact, although attempts have been made to extend this technology to metallic particles (e.g. EU project Sormen[4]), research contributions are mainly available for plastics particles (Fig. 5.3) [21, 22].

Commercial equipment for automatic optical sorting based on hyperspectral cameras can be found in the market. Although hyperspectral technologies can help characterizing the composition of metallic materials, current hyperspectral processing approaches involve poor characterization of the inherent variability of these materials and their visual appearance (optical texture, geometry, and pattern) of the particles

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[4] SORMEN—Innovative Separation Method for Non Ferrous Metal Waste from Electric and Electronic Equipment (WEEE) based on Multi- and Hyperspectral Identification project, 6FP Horizontal Research Activities Involving SMES Co-Operative Research, 2006.

[23]. Besides this, the high amount of data that is inherent to hyperspectral imaging implies slow data processing rate, which is not acceptable for real-time recycling applications [24–26]. Thus, new real-time hyperspectral models enclosing texture, optical pattern, component variability and adaptability to improve the overall recycling process are necessary.

5.3 Problem Statement and Research Approach

An approach to deal with the product, process and system co-evolution problem for recycling systems needs to satisfy the following requirements:

- in-line characterization of metal and non-metal materials composing the relevant waste flow;
- knowledge-based optimization and control of recycling processes, in view of the adjustment of the system parameters for the specific mixture under treatment;
- flexible and modular automation to increase shock-robustness via reconfiguration and modularity of machinery and systems;
- integrated software tools to support co-evolution related decision-making in industry;
- assessment of the sustainability of new technologies and proposal of suitable recycling business models for risk mitigation.

The proposed approach consists of the following technological and ICT-based solutions (hardware and software) to meet the previous requirements:

- in-line hyperspectral imaging technology to provide field data about the particles size, shape and material composition (Sect. 5.4.1);
- new process optimization and control models, software and code for the mechanical separation technologies based on CES (Sect. 5.4.2);
- scenario-based analysis techniques to decide under uncertainty what products to treat in the recycling system in a decision period and what are the target grade and recovery levels to be achieved for each material (Sect. 5.4.3);
- a new flexible and automated station to separate upfront the highest fraction of mixed metals and non-metals, thus enabling a more efficient process-chain (Sect. 5.4.4);

The developed solutions were demonstrated in prototypal applications (Sect. 5.4.4) and the applicability of the approach was tested in a real industrial case (Sect. 5.5), i.e. the De- and Re-manufacturing Pilot Plant at CNR-STIIMA (ex CNR-ITIA). The pilot plant is a fully automated, modular and reconfigurable solution involving integrated technologies for the disassembly, testing, reworking, shredding and mechanical separation of mechatronic products. The facility supports industrial research and innovation with the main purpose of recovering both functionality (when possible) and target materials from End-of-Life products.

5.4 Hardware, Software, Business Models and Prototypes

5.4.1 Hardware System

The developed Hyper Spectral Imaging (HSI) system enables the in-line recognition and classification of shredded products in terms of mixture composition (percentage of metal and non-metal fractions, shape and dimensional distribution) [27], with the aim to adapt the configuration and the working parameters of the downstream separation processes. In particular, the system provides feedback to trigger the control model of CES (i.e. drum speed, electrode voltage, feed rate and output stream splitter position), according to the specific mixture under treatment.

From a technological point of view, the main challenge consisted in the development of a robust and flexible imaging system for the in-line characterization of the metal and non-metal fraction of waste. The underpinning knowledge regarding spectral signatures of pure materials is derived from end-member collections, with cross-check performed by Scanning Electron Microscope (SEM) measurements.

The information about composition and geometry of the particles in the mixture made available by the developed vision system is used to feed a multi-body simulation model and an optimization and control module to get optimal separation parameters and improve the configurability of the recycling system.

The implemented vision system includes three main elements: (1) the hyperspectral camera, (2) the illumination system and (3) the transportation system. The conveyor speed, the image frame rate and binning are mutually aligned for the effective performance of the system.

5.4.2 Software System

The software tool controlling the vision system was implemented ad hoc in Matlab. The group of scripts is able to automatically control the camera acquisition and characterize the mixture in terms of composition, geometry and dimensional distribution. The software tool sends then this information to the separator to optimize the sorting control parameters. In particular, the following steps have been coded in the script:

1. radiometric calibration to relative reflectance;
2. removal of bad bands at the spectral edges;
3. bands compression using triangular fuzzy set;
4. background removal (conveyor belt);
5. compensation for the illumination;
6. spectral subset in order to focus only to a specific spectral region (optional);
7. waste mixture classification;
8. geometrical attributes extraction;
9. calculation of mixture composition statistics (percentage).

For the purpose of the simulation developments, granular flows involved in waste processing exhibit complex dynamical phenomena. Therefore, a custom simulation software based on multi-body dynamics was developed. Such a tool simulates the trajectory of thousands of processed particles, including mutual collision effects and their interaction with electric and magnetic fields in the CES and Eddy Current Separation (ECS) machines.

The large-scale nature of this type of simulation, along with the complexity of collision detection between heterogeneous shapes in three-dimensional space, advocated the adoption of innovative and efficient simulation algorithms backed by the theory of non-smooth dynamics, Measure Differential Inclusions (MDI) and Differential Variational Inequalities (DVI) [28]. The simulation software, available as open source C++ software, is written in C+ language and is dynamically linked with the multi-physics ProjectChrono library, whose features have been customized to meet the needs of this work [29]. A simplified 2D version of the simulation tools has been developed in Matlab as well [30].

Two approaches were implemented to provide a source of virtual waste flow in the simulation tool. The first approach consisted in pre-processing a sample of waste flow using the hyper-spectral video camera, hence obtaining a set of faceted particle shapes and corresponding materials that are sorted and replicated continuously within the virtual inlet during the simulation. The second one consisted in the generation of particles as random samples from user-defined multivariate distributions; to this end, an innovative system based on a hierarchical description of the probability space was designed [31].

An add-in for the SolidWorks CAD, using C+ language, was also designed to export coordinates, geometries, references and collision boundaries of the separating machines into a neutral file format to be processed by the simulator in a following phase. A further advancement came from the adoption of parallel computing hardware for accelerating the collision detection and the time integration [15].

5.4.3 Business Model Validation

Thanks to the new hardware and software technologies, the resulting flexible recycling systems are able to dynamically adapt the implemented recycling strategy to business conditions. This means that it will be possible not only to adapt process parameters to variations of volumes and characteristics of waste that will be required to treat over time, but also to select strategically—and source accordingly—the type of waste that should be treated to maximise the profit based on material pricing and availability of waste. However, a wider range of options and the uncertainty that is typical of the recycling context makes difficult to companies to fast decide what is the best strategy to be pursued. Thus, decision support tools able to indicate suitable business models and to predict economic performance under uncertain conditions are needed to dynamically address business operations and maximise profit.

A scenario analysis model was implemented for assessing the economic feasibility of the reconfigurable recycling system treating multiple waste product streams. The scenario analysis is capable of analysing possible future events by considering alternative probabilistic outcomes [32]. A base-case, optimistic and pessimistic scenario were defined and economic performances were assessed under each scenario calculating the Net Present Value (NPV) and the Pay Back Time (PBT).

Based on interviews to recycling companies and experts, two variables were selected as the main determinants of recycling economic performance: the relative volume of waste products to be treated in a time period (waste mix) and the market price of materials. Waste volume and mix may vary unpredictably due to fast products technology cycles, success (or failure) in regional tenders for treating specific waste over fixed time periods, new regulation, etc. Different types of waste contain different percentages of valuable materials and require different type of treatment processes which impact on costs. On the other hand, the market price of materials depends on their periodic demand and availability, thus determining the revenue that is made by selling recycled materials on the market. Scenarios were designed by making the hypothesis of average, favourable and unfavourable waste mixes according to their content of precious materials and of recycling cost. Such waste mixes were combined with three different levels of materials costs, considering positive and negative variations of prices from current levels (see Sect. 5.5.2).

5.4.4 Prototypes

A CPS platform was realised to integrate two workstations including *Vision System, Classification/Control Module* and *CES, Multi-Body Simulation Model and Optimization/Control Module* (Fig. 5.4).

The vision system workstation integrates an ImSpector V10E (Specim) working from 400 to 1000 nm, with a spectral sampling range from 0.78 to 6.27 nm/pixel, coupled with a CMOS sensor (1312 spatial × 768 spectral pixels). The camera is equipped with an OLE 23 fore objective lens with a focal length of 23 mm and a FOV of 25.7°. The HSI sensing device is a push-broom system working as a line scan camera providing full contiguous spectral information for each pixel in the line illuminated by two opposite slots housing 3 halogen lamps each, which emit in the spectral range 380–2200 nm. The implementation of the HSI system deals with the need to recognize the materials on-line, enabling the recycler to perform a continuous quantitative characterisation of mixture composition, thus avoiding time-consuming off-line sampling material characterization procedures.

The separation workstation integrates a Corona Electrostatic Separator Hamos KWS. The quality of the separation process is influenced by five controllable parameters: (i) electrode voltage and position; (ii) drum speed; (iii) output stream splitters position; (iv) material feed rate; and (v) feeder vibration. However, due to the complexity of the process, non-controllable effects, such as particle-particle interactions and impacts among particles and machine, influence the efficiency of the pro-

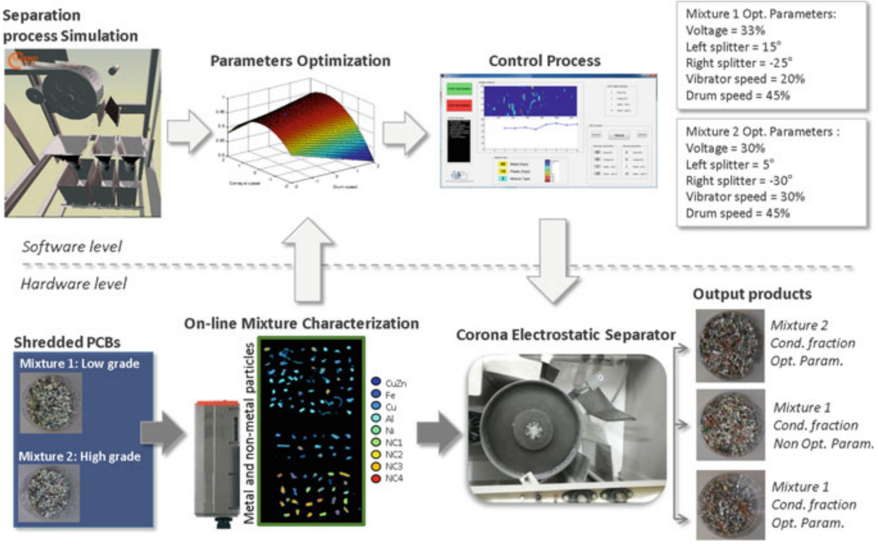
Fig. 5.4 Prototype for feed-forward control strategies: HSI workstation (right) and electrostatic separator (left). Implemented at the de- and re-manufacturing pilot plant of CNR-STIIMA (ex CNR-ITIA)

cess, providing contaminated output flows. For this reason, a multi-body simulation model of electrostatic separator process, considering particles attributes, trajectories, interaction and collision, has been developed. The whole system has been validated with experimental analyses, under different operational conditions (i.e. mixture type, machine working parameters).

Thanks to the integration between CES simulation model (that gives a prediction of particles trajectories) and the optimization and control modules, the optimal separation parameters are suggested to the operator for the mixture under treatment. A two-layer architecture integrated within the recycling process-chain supports the control, operation and reconfiguration of advanced multi-material de-manufacturing plants. This two-level approach is focused both on the process level and on the system level and considers the interconnections between physical and virtual entities (Fig. 5.5).

Data about the mixture (composition, geometrical attributes and dimensional distribution) gathered in real-time by HSI vision system are sent to the two-level modelling platform to enable the control of technologies and the reconfiguration of the recycling process chain according to the specific system and material state. A new software platform, controlled by the customized user interface shown in Fig. 5.6 has been designed and implemented to manage the information flow between software and hardware at system level. In this way, the whole process is automated and supervised. However, the operator can easily intervene in manual mode, if necessary.

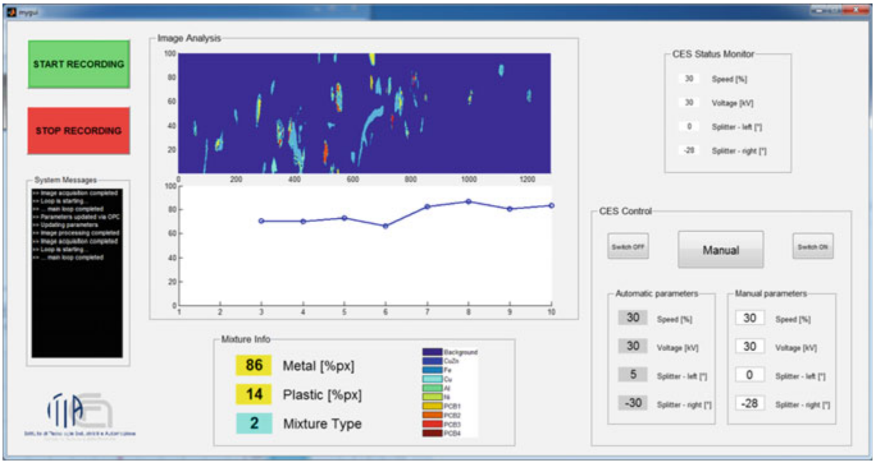
The implementation of a CPS platform significantly improves the adaptability of the recycling system and the recycling rates. It avoids losses of high-value materials, improves the information about the quality of recycled material and, as a consequence, its market value.



Mixture 1 Opt. Parameters:
Voltage = 33%
Left splitter = 15°
Right splitter = -25°
Vibrator speed = 20%
Drum speed = 45%

Mixture 2 Opt. Parameters :
Voltage = 30%
Left splitter = 5°
Right splitter = -30°
Vibrator speed = 30%
Drum speed = 45%

Fig. 5.5 Architecture of the CPS for online adaption of recycling processes



```
>> Image acquisition completed
>> Loop is starting...
>> ... main loop completed
>> Parameters updated via OPC
>> Updating parameters
>> Image processing completed
>> Image acquisition completed
>> Loop is starting...
>> ... main loop completed
```

CES Status Monitor
30 Speed [%]
30 Voltage [kV]
0 Splitter - left [°]
-28 Splitter - right [°]

Automatic parameters
30 Speed [%]
30 Voltage [kV]
5 Splitter - left [°]
-30 Splitter - right [°]

Manual parameters
30 Speed [%]
30 Voltage [kV]
0 Splitter - left [°]
-28 Splitter - right [°]

Mixture Info
86 Metal [%px]
14 Plastic [%px]
2 Mixture Type

Fig. 5.6 Graphical user interface for process control

The realised prototype demonstrates the benefits of the pursued integration approach in recycling systems, where high-cost and sophisticated control solutions would result inadequate due to technical (particles of different shape, size and composition) and economic reasons. The prototype represents a step towards the implementation of the HSI technology for a highly accurate classification of independent sets of wastes including metal and non-metal fraction undergoing mechanical treatment.

5.5 Industrial Testing and Results

5.5.1 *Industrial Case*

One of the most challenging modern recycling applications is the treatment of Waste from Electric and Electronic Equipment (WEEE) that represents the European waste with highest yearly average increase rate (5%). Such an increase was even higher in some European nations, e.g. in Italy the increase amounted to 30% in 2010 compared to the previous year (in terms of collected WEEE). Due to its material composition, WEEE represents an important source of recycled key-metals to be used for the production of advanced technological products. E-waste is a highly variable waste flow because of the wide range of products and material mixtures, which are in continue evolution due to fast technology cycles. For example, in small WEEEs (which in Italy are identified as "RAEE class 4"), Cathode Ray Tube (CRT) TVs, cellular phones and traditional HDD are rapidly being replaced by LCD/LED TVs, smart phones and SSD (Solid State Disks), respectively. Other new waste flows are rapidly entering the recycling streams, such as for example solar panels and tablet PCs. For the successful treatment of WEEE, besides being flexible, recycling systems must guarantee a high efficiency, since critical metals are present in small quantities (e.g. indium, palladium, ruthenium, gallium, tantalum, and platinum). For instance, indium is found in WEEE with an average weight of 39 mg in Notebooks, 79 mg in computer monitors and 254 mg in LCD TVs.

Considering these challenges, the scenario of WEEE was chosen as industrial case for the demonstration of the results of this research. In particular, Printed Circuit Boards (PCB) were chosen as reference WEEE products. PCBs are one of the key and most common components present in the majority of WEEEs. Critical and high-value metals (such as copper, tin, nickel, gold and silver) account for 25–40% of their total weight composition. The rest of materials (60–75% in weight) are ceramics, plastics and glass fibres. PCBs, which are the major constituent of the obsolete and discarded electronic scrap, account approximately for 3–6% of the total WEEE mass [33, 34].

PCBs are evolving fast from the technological point of view (from large high-grade matrixes into small, compact and medium grade products). For this study, PCBs disassembled from End-of-Life household appliances (e.g. washing machines) have been used and a representative sample of different models has been selected to be processed (Fig. 5.7).

5.5.2 *Vision System and Material Separation*

The experiments have been carried out in a real life demonstrator including two workstations: the vision system and the separation machine (see Sect. 5.4.4).

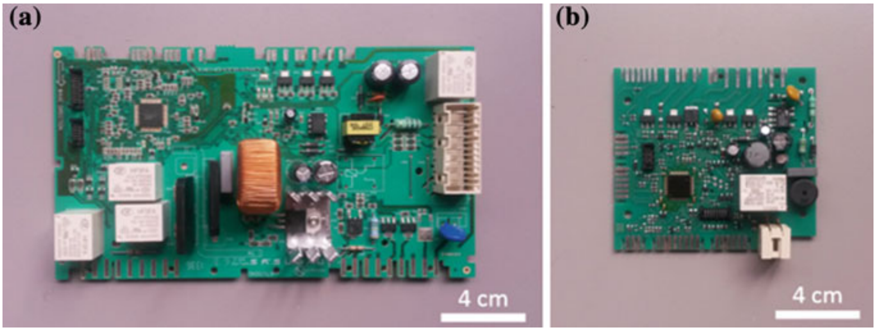


Fig. 5.7 Selected PCBs from EoL washing machines of different brands (**a**) and (**b**)

Two different sample sets have been prepared to: (i) train and test the HSI system and (ii) test the HSI system for the feed-forward control of separation processes. For both sets, the first part of the preparation procedure consisted of a two-stage shredding by using hammer and cutter mills, followed by sieving treatment. The liberated fraction (average diameter below 1 mm) was thus separated by the CES to obtain two fractions: conductive and non-conductive. For the HSI system training and validation, several metal and non-metal particles have been manually sorted from those output fractions according to their colours (conductive: yellowish, greyish or reddish; non-conductive: greenish), to be further analysed by using Scanner Electron Microscope (SEM).

An experiment was designed to assess the performance of the vision system for the mixture characterization. Fine metal particles with average size smaller than 2 mm were manually selected from shredded PCBs, sorted based on their colour and size, and placed on two different 5 cm × 5 cm tiles in a 9 by 7 grid configuration (Fig. 5.8) [27].

The particles were also analysed with a scanning electron microscope (SEM) which provided information on their chemical composition. This information was used for the choice of training samples and for the accuracy assessment of classifications. The particles were classified according to the procedure, testing several different combinations of both classification algorithms and methods for the illumination compensation. The best results were achieved using algorithms which take into accounts spectral correlations through a covariance matrix, such as Mahalanobis Distance and Maximum Likelihood [35], and with the method for illumination compensation proposed by Stokman and Gevers [36]. The best classifications showed values of overall accuracy (OA) and kappa coefficient (KC) greater than 95% and 0.95, respectively.

Finally, the developed multi-body particle simulation tools were used to perform off-line optimization of the on-line control algorithms of the separation processes [37]. A virtual inlet was defined to generate a continuous flow of particles in the 3D simulated environment (given input statistical distribution about particle size, density, material and shape, according to the approach that presented in [31]). Gen-

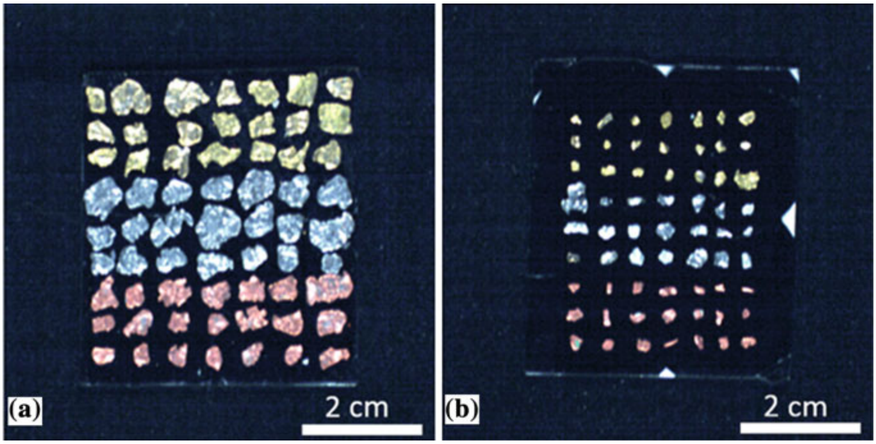


Fig. 5.8 True colours images of shredded PCBs of two selected metal fractions (**a**) and (**b**)

erated particles, in the order of tenths of thousands, underwent the simulated CES or ECS separation and finally the performance of the separation was evaluated by computing the statistical distribution of the ballistic separation in a post-processing stage, similarly to a Montecarlo method. Results of the processed multibody simulations, namely the probability density functions of the lengths of the trajectories for different materials, were discussed in detail in [28, 29] where the comparison against experimental data (sampled by hand using sieves and bins) shows that the multibody model can be used as a digital twin of the real separation process. The simulation of even five seconds of separation might involve large amounts of particles, thus leading to a computational bottleneck that, in the presented scenario, required up to one hour of computation. Therefore new classes of DVI solvers were used to improve the computational efficiency [38–40]. In addition, GPU parallel computing was adopted as discussed in [15].

5.5.3 Business Sustainability

The business sustainability of new flexible recycling technology (with the capacity of 400 kt/year) was simulated considering multiple waste flow that can be optimally treated in different time periods.

Besides PCBs, other selected waste flows were cellular phone, non-hazardous LED lamps and incandescent lamps. Considering material value, within the three types of product, PCB and cellular phone are characterised by higher material value compared to lamps.

The following scenarios were set for waste mix:

- *Optimistic scenario*, waste composed of 45% PCBs, 45% cellular phones and 10% lamps.
- *Base scenario*, waste composed of 33.3% PCBs, 33.3% cellular phones and 33.3% lamps.
- *Pessimistic scenario*, waste composed of 70% lamps, 15% cellular phones and 15% PCBs.

The following scenarios were set for materials price:

- *Optimistic scenario*, material price is 20% higher than material price at the time of the research.
- *Base scenario*, material price remains equal to the material price at the time of the research.
- *Pessimistic scenario*, material price is 20% lower than material price at the time of the research.

The combination of the possible outcomes leads to nine global scenarios. A hypothetic recycling company already operating in the market was taken in consideration to assess the acquisition of the new flexible technologies for business expansion. Investment costs, operation costs and performance parameters (such as system capability, lead time, grade, etc.) were estimated through experimental tests carried out at the CNR-STIIMA (ex CNR-ITIA) pilot plant [41] equipped with the new technologies and relying on data from recycling literature.

Table 5.1 reports the results of the Scenario Analysis for the described industrial case.

As it can be noticed, under the hypotheses of the study, the investment in new flexible technologies able to efficiently treat multiple waste streams appears sustainable in all scenarios (NPV at 10 years ranges from 7,457,343 euro in the pessimistic scenario to 13,502,507 euro in the optimistic one) and is repaid after the first year of operation. These results confirm the high business potential of flexible recycling plants.

Table 5.1 Scenario analysis of the business model validation

			Volume of the mix [euro]		
			Pessimistic scenario	Base scenario	Optimistic scenario
Material price	Pessimistic scenario	NPV(10)	7,457,343	9,155,943	10,362,141
		PBT	1	1	1
	Base scenario	NPV(10)	8,424,074	10,493,888	11,958,429
		PBT	1	1	1
	Optimistic scenario	NPV(10)	9,232,109	11,739,148	13,502,507
		PBT	1	1	1

5.6 Conclusions and Future Research

Circular Economy represents an innovative paradigm for sustainable manufacturing [42]. Relying on technology and business model innovation, the Circular Economy concept aims at maximising the use of products and materials. Recycling is one of the strategies that can be pursued in circular economy, together with re-use and remanufacturing. Through recycling, critical materials and key-metals can be recovered from post-use products when they can not be re-used or remanufactured.

Recycling systems are nowadays very rigid in their design and they do not allow dynamic adaptation of process parameters to different types of waste. For this reason, the performance of recycling plants is often sub-optimal. With the goal of developing a new generation of flexible recycling systems, new hardware and software solutions were developed in this study for the dynamic adaptation of process parameters to different type of waste. The Hyper Spectral Imaging (HSI) system and the software tool for the control of the sorting parameters based on a multi-body simulation model were demonstrated in a prototype at the De- and Re-manufacturing pilot plant of CNR-STIIMA (ex CNR-ITIA).

Business sustainability of flexible recycling plants based on innovative technical solutions was assessed as well. The selected industrial scenario is the recycling of WEEE, which poses significant challenges because of the high content of critical and key-metals and of the variability generated by rapid technology cycles. A scenario analysis model was developed to preliminary assess the economic sustainability of flexible technologies under the uncertainty deriving from the variability of future waste mixes and the turbulence of material prices. Under the hypotheses of the analysis, the investment in flexible technologies appears sustainable and very promising in all the simulated industrial scenarios, confirming the high business potential of flexible recycling technologies.

The conclusions of this research are aligned with some studies on other waste streams (e.g. in the recycling of construction and demolition waste [43] and of vehicle waste [44]). Results of the scenario analysis support the strategic importance of establishing reconfigurable recycling system due to their higher profitability, which should be achieved through the increase of quality of recovered materials [44].

This study has some limitations. Firstly, developed technologies were tested with a limited number of waste types and the wider capability of real-time adaptation to rapidly-changing waste flows was not extensively tested. Secondly, the economic assessment relied on data coming from literature and on the estimation of some costs derived from experimental tests and pilot infrastructure investment, which could differ from real industrial environment conditions. Further details on this research are reported in [31, 45–47].

This study provided first prototype results towards the introduction of flexible recycling systems in industry through HSI technology for the classification of independent sets of WEEE with high level of accuracy. Future technology developments will be aimed at:

- improving the spectra database, increasing the number of reference spectra both for metals and non-metals;
- addressing the problem of dark particles, which were not considered in this work;
- integrating a wider set of algorithms for materials identification to improve the workflow flexibility and the process performance;
- improving the data elaboration step to speed-up the procedure and enable the real-time/on-line applications.

In addition, the business assessment of new technologies will be improved through the introduction of more accurate cost and revenue structures based on a wider set of experiments and the introduction of a higher number of industrial scenarios.

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