TREASURE

D5.2: Pilot-scale reconfiguration, testing and optimization of a semi-automated PCB disassembly process

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EXECUTIVE SUMMARY

The objective of TREASURE project is to offer an opportunity to make the automotive sector more circular. This objective is pursued with the realisation of tools that support the development of a circular supply chain within the possibility of testing different technologies. As already identified in the precursor FENIX project, the Key Enabling Technologies (KETs) can be integrated into various processes to obtain real benefits and to improve the efficient recovery of secondary resources. Among the KETs in this deliverable we will see how computer vision, AI, simulation, and collaborative robotics can be integrated to support activities in the context of Industry 4.0, and how they are key to achieving increased efficiency and repeatability of certain complex operations such as PCB disassembly.

The focus of deliverable D5.2 is on optimizing and testing the semi-automated PCB disassembly pilot. Building on what was accomplished in Task 5.1, Task 5.2 will focus on resolving the complexities inherent in disassembly activities by attempting to implement an efficient and flexible system for recovering critical materials from car electronics and providing all necessary support to the operator during operations.

Since physical disassembly of a PCB is a complex task, it will be necessary to briefly discuss the critical issues related to it and the state of the art of the various technologies used in this type of application. For this reason, Section 2 of this deliverable will briefly discuss HREs, computer vision and AI systems for image classification, and the examples of facilities for physical disassembly of PCBs received in the literature to highlight the critical issues of this procedure and define the challenges to be overcome to achieve an efficient and sustainable process.

In section 3, we will briefly talk about the Industry 4.0 Laboratory at the Politecnico di Milano and then show the tools and technologies that will be used to build the pilot plant. We will talk about why they were chosen, analysing their trade-offs, and discussing how they can be exploited to support the operator during the disassembly phase.

In section 4 we will discuss the tests performed to define a correct disassembly approach of the PCBs and propose a first configuration for the pilot plant. A Computer Vision algorithm suitable for detecting the presence of SMD components and guiding the cobot in semi-automated disassembly operation to remove Surface Mounted Device (SMD) will be proposed in addition to an application of the cobot that, with the Learning Behaviour described in deliverable D5.1, allows the removal of Trough Hole (TH) components from the board after it has been brought to an appropriate temperature.

In Section 5 we will discuss the critical issues and problems of the previous configuration, and a new optimized model will be proposed that allows a relatively simple and cost-effective solution for this type of application while highlighting its critical issues and strengths.

In the end, Section 6 will discuss the possible evolutions of this solution with the integration of the technologies mentioned in the introduction aimed at optimizing and refining the proposed solutions, trying to chart the course of future work on the plant.

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1. Introduction

1.1. Project Overview

The project is focused on recovering the electronic systems, as microcomputers and electronic components, present in modern cars that represent from 30% to 50% of the total vehicle cost. The main problematics arose in the recovery process regard mainly the End-Of-Life (EoL) of the product within difficulties in the implementation of the Circular Economy (CE) in this sector: the EoL is not well connected with the Beginning-of-Life (BoL) and the data about materials embedded in cars are partially accessible from all the actors. This project wants to make use of the Industry 4.0 enablers to deal with those problems realizing an AI-based scenario assessment tool that can support the development of CE while involving all the main actors and practically demonstrating the benefits with case studies.

1.2. Scope of the deliverable

The semi-automated PCB disassembly pilot's optimization and testing are the main objectives of deliverable D5.2. Building on what was achieved in Task 5.1, Task 5.2 will concentrate on addressing the challenges posed by disassembly operations by attempting to implement an effective and adaptable system for recovering vital components from automotive electronics and providing the operator with all necessary assistance throughout operations.

1.3. Contributions to other WPs

This deliverable starts as a development of what was defined in deliverable 5.1 "Simulation of semi-automated PCB disassembly processes" by implementing what was previously defined and trying to optimise the disassembly procedures.

The pilot will then be integrated into the TREASURE Platform following the architecture described in D4.1. Many of the considerations made from the point of view of recycling performance take their cue and information from what is described in D3.3 "Recyclability Analysis" trying to exploit the information obtained to guide the development of disassembly processes.

Deliverable 5.2 is also developed closely with downstream recycling practices, with the facility described in D5.3 "Simulation and lab-scaled testing of the materials recovery processes", taking into account information on the possible recovery of materials from recycling processes and thus selecting the most suitable electronic components.

2. Overview of PCBs disassembly and related technologies

2.1. Overview of the complex problem of PCBs disassembly

Even though it is now evident that WEEE is an excellent secondary source of CRM and rare earths, industrial-scale recycling technologies today rely on recovering only those materials found in higher concentrations. Industrial recycling processes, in fact, as shown in deliverable 3.3, achieve very low performance in terms of recovering those materials found in lower concentrations on the board to be recycled. The low performance in terms of recovery of these materials, again from deliverable 3.3, is because some precious materials are present on the electronic boards but in very low concentrations with respect to the total mass, thus making the industrial process focus on the recovery of materials present in greater quantities. Disassembly at component level would therefore allow for greater concentration and separation of materials, thus achieving higher recycling performance and enabling the recovery of those materials that would otherwise be lost in classical recycling techniques. Although the disassembly of PCBs is a topic that has already been dealt within the literature, to date it has not yet been possible to achieve an efficient and profitable system. In fact, this practice presents numerous criticalities from both a technical and an economic point of view. The low concentration of rare materials recoverable from the boards in fact requires the ability to work with tonnes of materials in order to properly feed the optimised recycling processes. Speaking of previously realised plants, one can mention (Zebedin, H., Daichendt, K., & Kopacek, P. 2001), one of the very first electronics disassembly plants. The implant, in the form of a cell, consists of a computer vision station, a station with a laser desolder, one with a robot for removing components, a preheating plate and another robot. The station is hand-loaded and although it is one of the first steps in solving this problem, it is very expensive, especially considering the time frame in which it was built. Another approach that can be mentioned is (Park, S., Kim, S., Han, Y., & Park, J. 2015) where a destructive and faster approach is taken. The boards are placed on a feeder that runs them under infrared lamps to melt the solder and then passes through rotating metal brushes to remove the components. Although the solution is relatively inexpensive and efficient, it does not solve the problem of sorting the components, which is crucial for optimising recycling processes. The technological challenges are therefore numerous, starting with the fact that information on the composition of electronic boards is often secreted and not accessible, especially in the automotive sector, thus necessitating the development of tools capable of generating or retrieving this information a posteriori. PCBs are also complex devices from both a physical and chemical point of view, so finding the best solution to disassemble them is complex; a thorough knowledge of the structure of such devices is required in order to be able to choose the best solution since each of them has inherent trade-offs, and if we also consider the very high variability of electronic boards, it is evident how complex the realisation of a flexible solution is. Speed and energy efficiency are certainly parameters to be considered as well as the choice of destructive or non-destructive approaches. It must also be considered that an operator may be exposed to hazards from the selected disassembly methods. Heat treatments in fact, when exceeding a certain temperature, release chemical elements into the atmosphere that are potentially harmful to both the environment and the operator.

In the light of the above, the problem of disassembling PCBs is a complex and multidisciplinary problem that does not currently have a solution that can be applied on an industrial scale. Nonetheless, thanks to the use of the new technologies available in Industry 4.0, it will be possible to come closer to an optimal solution, which we will propose within this deliverable, and for this reason we will find below a brief excursus on the technologies that can be used in this field.

2.2. Computer Vision and AI

As pointed out in section 2.1, one of the most critical aspects in the disassembly of PCBs is the recovery of related information. Often this information is in fact lost in the long electronics production chain, while at other times the related information is deliberately protected by industrial secrecy and not accessible. Although efforts can be made to sensitise and guide manufacturers to share this information with recyclers, this scenario still seems distant. It is therefore necessary to develop technological solutions to retrieve it a posteriori so that it can be used in disassembly processes. For this task, Computer Vision and AI, tools capable of extracting the desired information from PCB images, are essential. In this deliverable, we will see a first application of Computer Vision to isolate components on the board and discuss how an AI-based component classifier is one of the key technologies to be developed to develop an efficient system. Since, in fact, CRMs are usually contained in specific components, having a system capable of recognising the critical components present on a generic PCB would make it possible to guide the disassembly processes towards the ones that contain the materials to be recovered. This would help in the realisation of an extremely flexible system capable of selecting only the critical components to be removed, avoiding removing what can be handled within the classic electronics recycling systems, thus saving time and energy. We will go into detail later how to implement this technology within this application. Numerous attempts have been made in the literature to implement an AI capable of classifying components, some of them even successfully but applied in the field of PCB assembly, although from what we can gather from these studies, the problem is particularly complex: *“the object class imbalance in the PCB assembly scene, the multi-scale feature imbalance, and the positive/negative sample imbalance in the CNN have become critical problems restricting object detection performance.”* (Li, J., Chen, Y., Li, W., & Gu, J. 2022) and again “*due to the precise and small characteristics of electronic components, their identification, classification, and localization become a difficult task in the reuse process.” (*Chen, J., Bao, E., Pan, J., Chen, J., Bao, E., & Pan, J. 2022).

2.3. Collaborative Robotic

A cobot is defined in the ISO/TS 15066:2016 (ISO/TS 15066:2016 - Robots and robotic devices – Collaborative robots. 2016. url: https://www.iso.org/standard/62996.html) as “*a robot that can be used in a collaborative operation*”, defined in turn as an operation “*where purposely designed robots work in direct cooperation with human within a defined workspace*”.

The ISO 10218 safety standard (the ISO 10218-1:2011- Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots. 2011 url: https://cutt.ly/BNuekXF) and the RIA ISO/TS 15066 technical specification define the safety functions and performance of a cobot, within four different Collaborative Robot Operations:

- *Safety-rated monitored stop*, that pauses a robot’s motion while an operator is in the collaborative workspace;

- *Hand-guiding operation*, which allows an operator to move the cobot to a specific point without any knowledge.

- *Speed & separation monitoring*, which allows the cobot to move with a certain speed until the human and the cobot maintain a certain distance;

- *Power and force limiting*, which allows for detection of the physical contact between the robot system (including the workpiece) and the operator, that can occur either intentionally or unintentionally. Of course, those contact should be limited to the ones planned to guarantee the highest safety level possible.

The operative modes above create new opportunities for a human to work in cooperation with a robotic system but pose different limitations to the operative possibility of the systems.

The HRC is seen as one of the major research topics that can support CE with the development of remanufacturing and recycling frameworks among all the solutions that can support CE in the Industry 4.0 context (Rocca et al., 2020). (Daneshmand et al., 2022). The ability to divide and allocate work differently is made possible by the presence of both humans and robots. While the robot can do all harmful activities, humans can correctly direct the robot and handle higher-value tasks, leading to greater job satisfaction (Alvarez-de-los-Mozos et al., 2020).

Even though many of the HRC-related features are still difficult for industrial application, it is still seen as essential for the creation of new procedures that must lower WEEE waste (Alvarez-de-los-Mozos et al., 2020). The freedom offered by cobots, which may operate without any obstructions close to the operator, makes it possible to design procedures that, in turn, are versatile and can adjust to various disassembly requirements. (Kerin & Pham, 2019).

Focusing on the disassembly tasks to be completed for the project, the cobot can assist the operator in automating the processes when it comes to disassembling various types of PCBs. (Cesta et al., 2016). Though the number of PCBs that may be dismantled is quite vast, a human is still required to direct the cobot when it comes to a new set of tasks that need to be carried out, at least in the early stages of the process development. In fact, it will be necessary to discuss whether the presence of a human operator is still required at the end of the development of this application. Indeed, by developing a flexible solution, operator involvement could be minimised and perhaps reserved for the control of several PCB disassembly systems simultaneously. Dealing with narrow profit margins in this type of application, the cost of an operator can significantly shift the profitability assessment of the system.

3. The Industry 4.0 Laboratory and tools

3.1. The Industry 4.0 Laboratory of Politecnico di Milano

This section introduces the Industry 4.0 Laboratory (I4.0 Lab) owned by the Manufacturing Group of the Department of Management, Economics, and Industrial Engineering of Politecnico di Milano (www.polimi.it).

(a) (b)

Figure 1 - Industry 4.0 Laboratory at the Politecnico di Milano

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As well explained by (Fumagalli et al., 2013), "*I4.0 Lab is a tangible physical entity to carry out research activities in a "real-like" Industry4.0 environment. I4.0 Lab represents a central pillar for Industry 4.0 awareness and knowledge diffusion, both for industrial network and for research and academic network*". The laboratory collects different types of systems to carry out different research activities: a complete production line in Figure 1 (a), aligned with the industry 4.0 state-of-the-art technologies; an AGV for managing logistic informative system and a Franka Emika Panda Cobot in Figure 1 (b). This section describes first the cobot used for the task and how it can be controlled, then the semi-automated PCB disassembly process developed for the FENIX project is presented as a starting point for the design of the Cobot Interface for the TREASURE project. We have also recently introduced a new section in the laboratory. This section was developed because of the needs identified by the TREASURE project. This is how the CV Lab4.0 came to be known. It is a purpose-built space that allows for excellent image acquisition and all the necessary infrastructure to process the acquired images. Here in figure 2 is reported his first set-up.

Figure 2 – The CV Lab4.0

3.2. The UR5e

We recently received and installed the Universal Robot UR5e, the cobot acquired explicitly for the Treasure project. The GUI and all the functionalities developed in D5.1 were transferred from the Panda Cobot to the UR5e, which, following an ad hoc configuration, is controlled externally by a workstation working in the ROS environment. The simulation system has also been revised with the possibility of simulating the cobot in the Gazebo environment, a software focused on simulation and used as a standard in much research and non-research applications, thanks to the possibility of recreating real scenarios also regarding the physics of the objects inserted in the simulation context.

Figure 3 – The UR5e

The robot is also equipped with two different end-effectors specially selected to perform operations to support the disassembly of PCBs:

1) A Robotic Hand E gripper, a two-finger gripper with long stroke and suitable for precision machining

2) A custom 3D-printed tool-holder designed to conveniently mount the air desolder on the UR5e's flange


(a) (b)

Figure 4 – The air desolder (a) and the Hand-E gripper (b)

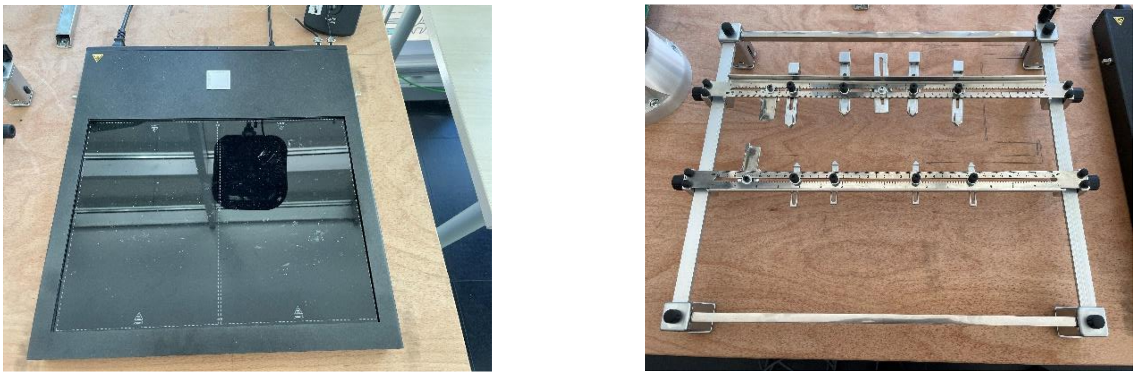
The gripper, being an aftermarket appendage unlike the Panda Cobot's gripper, which is integrated and modelled as an integral part of the cobot, is designed for plug-and-play integration only with the cobot's control-unit, so it was necessary to find suitable drivers to control it via the ROS environment and to acquire the correct model to be inserted into the simulation environment. This type of gripper is ideal for precision assembly tasks and working in industrial environments and comes with a set of different fingers depending on the shape of the objects to be worked with. These features make it particularly suitable for an application such as the disassembly of PCBs where great precision and flexibility is required due to the variance in size of electronic components. As far as the custom tool holder is concerned, it was sufficient to design and construct a robust tool holder that can be attached by screws to the flange of the UR5e's end-effector and make considerations on the reference system to align that of the cobot with the tool tip.

3.3. The Automatic Tool Changer

We have also recently received a TripleA Robotics WM1-K-05-00, an automatic tool changer developed specifically for cobots and capable of automatically replacing the tool if the operations to be performed change. The kit includes adapters that can be placed between the cobot flange and the tool, allowing the tool to be automatically unhooked and hooked using the support provided. To attach the supports to the workbench on which the cobot sits, we fabricated a stainless-steel frame which was then screwed to the tabletop. The system is currently being tested and we are still waiting for a cable so that we can bridge the connection between the adapter and the gripper. The end-effectors, and in particular the electronic ones, although not complex in terms of assembly, require special care when handling the electronic connectors (pins), which are extremely delicate and complex to replace if they break. Considering the time required for the operator to carry out a tool change and the skills required, this will allow substantial savings in terms of setup time and operator training, while also ensuring greater flexibility.

3.4. The Preheating Plate

To disassemble the boards, an air desoldering unit of classic use for PCB rework applications and a JBC preheating plate of a suitable size to accommodate boards of various sizes were also chosen. The board was chosen for its ability to control temperature in a variety of ways, being able to define temperature profiles or work with control and reference thermocouples. The board allows a maximum temperature to rise of 2C°/s, guaranteeing gradual heating of the PCB without damaging it. The plate reaches a maximum of 250°C, a temperature that allows, in the case of correct application, to desolder the components from the board and not reach temperatures that cause the emission of toxic and/or polluting substances. This allows for a safe heat treatment that allows for the presence of an operator and avoids damage to the PCBs. Unfortunately, the trade-off lies in the time required to bring the boards up to temperature, which averages around 600s.



(a) (b)

Figure 5 – The preheating plate (a) and the modified frame (b)

Control of the board can be done via the supplied control interface or connected via Ethernet to a workstation or robot, proving to be a precise and flexible tool for this type of application. The board is also supplied with a modular frame that makes it possible to clamp a wide variety of PCBs. The frame was subsequently modified by us to make certain interactions of the cobot and operator easier by stiffening certain sections and creating supports to prevent the PCB from slipping out of the holder if external forces are applied.

3.5. Camera and CV Algorithm

A hand-eye system, i.e., a system that exploits information from computer vision systems in combination with the flexibility and precision of robots, greatly increases the potential of a cobot, especially in a context such as PCB disassembly. For this reason, we integrated an Intel Depth Camera D435i with the cobot.

Figure 6 – The Intel Depth Camera D435i

This type of camera has a built-in IMU capable of processing image depth data locally as well as capturing an RGB image. This type of information is particularly useful in the field of PCB disassembly as it can be processed with the correct Computer Vision and AI tools to extract useful features for the automatic operations to be performed by the cobot. Although this type of camera is particularly accurate, it must be remembered that to increase the effectiveness and precision of any image processing algorithm, it is necessary to minimise the issues surrounding incorrect lighting. Therefore, within the Industry 4.0 Lab we set up a photographic set in a windowless room to improve the quality of the acquired images and reduce any kind of noise or disturbance due to sub-optimal lighting. In addition, in the case of image acquisition of PCBs, one often encounters the phenomenon of reflectance, a problem that can be mitigated with the help of matting sprays and an optimal angle of the light source.

4. First Plant Configuration

4.1. Preliminary Tests

The first phase of the implementation was dedicated to extensive testing in the disassembly of PCBs to better understand their characteristics. A short literature study was also conducted to identify existing methodologies and evaluate their performance. Since there are numerous methodologies discussed in the literature regarding the physical separation of electronic components from the board substrate, the most suitable technique can only be elected according to the type of application in which it is intended to proceed. Physical separation techniques can be distinguished into destructive and non-destructive. The former focuses on maximizing the throughput of processed boards, the latter on recovering intact components and not damaging the board from which they are taken. In the case of selective disassembly, a non-destructive approach appears to have many benefits and to be better suited to the context in which the pilot plant was intended to be developed. The possibility of separating and processing components containing high concentrations of CRMs is indeed a great added value that currently seems to be exploitable only with non-destructive approaches. Furthermore, considering the presence of the operator in the working environment, it is preferable to select physical separation methods that minimize exposure to human health hazards. Following these considerations, it was decided to opt for thermal treatment of PCBs, which although not the most efficient method in terms of time is certainly the most efficient in terms of simplicity and cost. The first tests were carried out in the laboratory with an air desoldering machine and an industrial hair dryer. These preliminary tests served to identify the first characteristics of the boards and their behaviour when thermally treated. The first consideration to be made concerns the structural difference of the electronic components on the boards. By identifying them by macro-category, we can distinguish them into two groups:

- Trough Hole (TH): generally larger components present on the board and fewer in number are soldered by means of pins that pass through the board and are soldered to the back; they also have in some cases additional fastening systems to the board such as plastic clip or metal clips.

- Surface Mounted Device (SMD): components of extremely variable size in usually larger numbers; they are soldered onto the surface of the board and in the case of some boards under consideration are present on both sides of the board.

It quickly became clear that the greatest difficulties in disassembly are related to THs, which, being generally larger than SMDs and having numerous pins to be desoldered, require an even temperature distribution over the entire soldering area. SMDs, on the other hand, due to their generally smaller size and less soldering agent, are quicker to separate from the board by heat treatment. The optimum temperature range has also been defined to be able to melt the soldering agent without, however, reaching excessively high temperatures that would lead to the pyrolysis of some components with the consequent release of potentially harmful substances. The material used for soldering in the case of modern electronic boards consists mainly of tin with the addition of small percentages of silver and copper, and we have observed and checked in the literature that a range between 217 and 225 °C can be considered optimal for desoldering components from the board. To be able to disassemble the TH components, it immediately became necessary to use a preheating plate described in Sect. 1. Tests were therefore carried out to develop a suitable temperature profile and to estimate the time required to reach the target temperature. A critical aspect was the different heat absorption of the boards depending on their mass, mounted components, and thickness. This causes differences in terms of time to reach the target temperature. For the boards examined, i.e., those from the combi-instruments, the time was around 600s. This time is high, but it was found that in the case of boards with components on both sides, it is not necessary to reheat the board to proceed with disassembly. The combi-instrument boards and the other boards in exam were therefore completely disassembled, and the procedures were documented in an Excel file in the appendix, in which mass balances were carried out and an attempt made to categorize all SMD components present and to report their masses for each board examined.

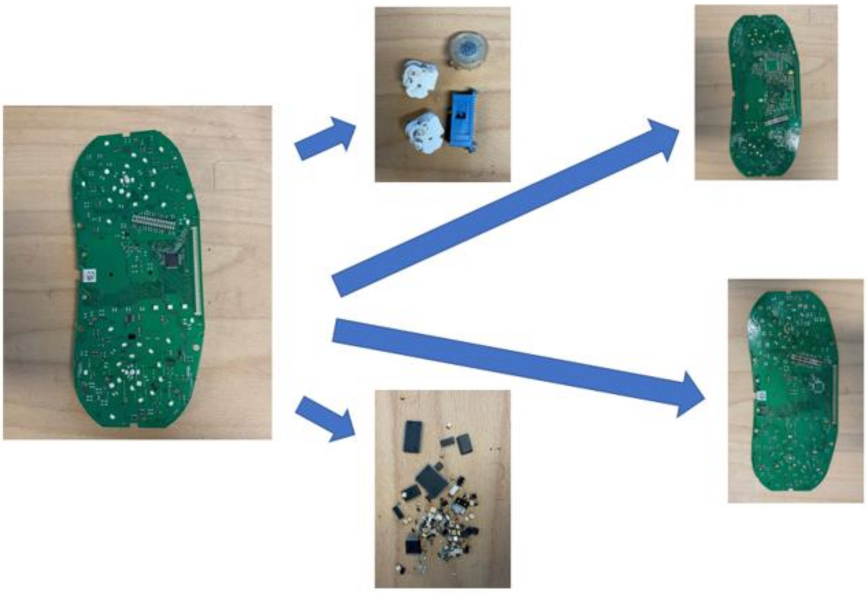


Figure 7 – The board decomposed in its components

The categorization is a first attempt to map the content in terms of board components, but since SMD components come in almost microscopic sizes and the shapes and colours do not differ, classifying them is, in some cases, quite complex. Attempting to obtain this type of data is essential to investigate the margins in the case of an industrial implementation; we will discuss this in more detail in Section 6.

4.2. Structure of Proposed Solution

Once the disassembly tests had been carried out and strengthened by the information gathered, we started to implement the pilot plant's Automatic Behaviour, i.e., the management of all operations to support the operator. Given the nature of PCBs and the presence of the two macro-families of components, it immediately became apparent that these two categories needed to be treated differently. SMD components, in fact, are easy to remove with an air desoldering device which, if correctly positioned, allows SMD components to be disassembled in the heated area in about 12s. As far as TH components are concerned, on the other hand, it appeared necessary to use the preheating plate in order to distribute the temperature evenly over the component pins. For this reason, the disassembly procedure is proposed in two different stages: the first to remove the TH components and the second to remove the SMDs. As shown in the table, the two procedures will be merged into a single process, which, thanks to the presence of the changer tool, will make it possible to switch from one phase to the other, reducing setup time to a minimum. The complete structure is proposed in the table below:

User	Cobot	GUI	Camera	Activity
x	x		x	A camera then scans the PCB a first time with all components: • It divides space into areas labelled as 0 (no SMD detected) or a number greater than 0 that assess the presence of SMD; • The cobot moves skipping the 0s and stops where the number is greater than 0 to perform the desoldering operation. Once the operation is done the operator presses "Enter" and the cobot continues the routine as explained before.
	x	x		The board is placed on the pre-heated board to desolder the through hole components which will be extracted by the cobot via it's end effector.

4.3. Treatment of SMDs components

To be able to disassemble the SMDs, it was decided to use a hand-eye system that was able to quickly desolder the SMDs with minimal operator support. To be able to realise this type of application, it was necessary to create an algorithm that, starting from the acquired images of the PCBs, was able to reconstruct and communicate the presence of SMD components to the cobot. The first step was to set up an optimal environment for the acquisition of PCB images. For this reason, as mentioned in section 3, the acquisitions were carried out within the Industry 4.0 Lab room specifically created for this type of application. From the first acquisitions, it was in fact essential to eliminate any kind of disturbance in this type of application, since some parts of the board have reflective properties and many SMD components are very small. Once the setup was done, we developed an algorithm capable of extracting the desired features from the board. The algorithm was developed in Python with the OpenCV library, a popular library used for computer vision applications. Since, as previously discussed, the optimal solution lies in the implementation of a complex AI algorithm, the first step towards this goal was to design a lean and efficient algorithm for analysing boards without being overly complex. The algorithm is a pipeline of several algorithms that applied in cascade extract the contours of all components of the board.

Figure 8 – Pipeline algorithm

Regarding the interchangeability of the algorithm, we initially focused on the cards of the combi-instrument. In fact, the first algorithm in the pipeline, i.e., HSV Tresholding, functions as a color filter and serves to obscure the green substrate of the board from other components. This filter, in the case of boards without a green substrate, must be color-calibrated in order to isolate the components from the substrate. An automatic approach can be implemented to make this type of filter adaptive, but having already outlined an optimal solution, further development may not be so sensible.

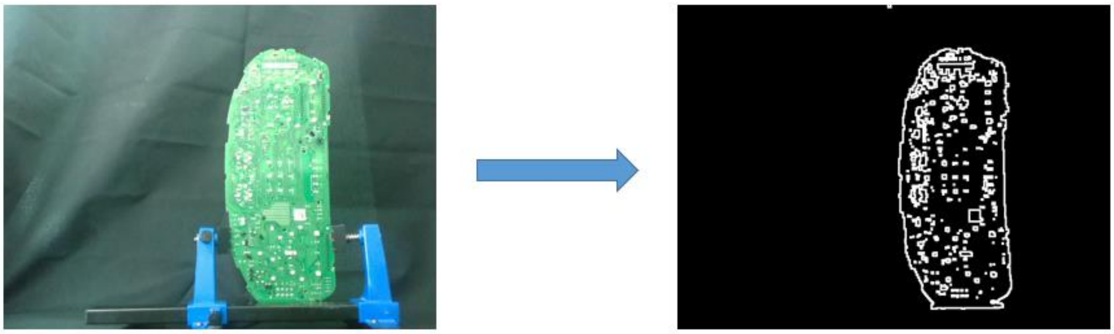
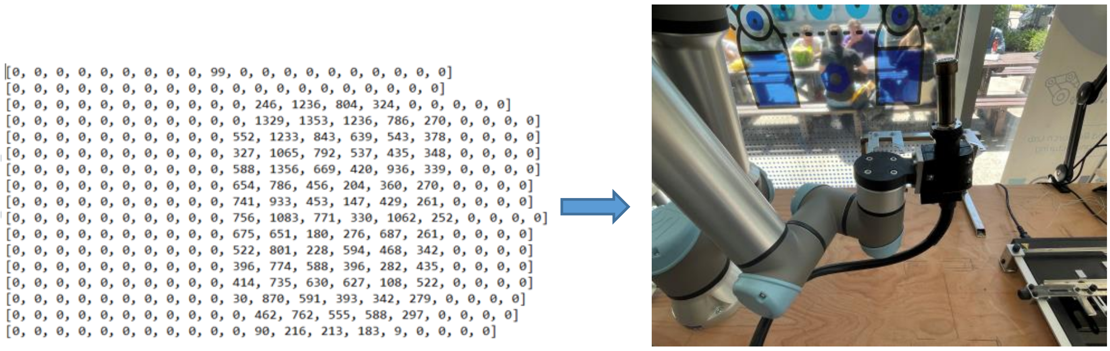


Figure 9 – Processed image

Once a processed image had been obtained, i.e., showing the contours of the SMD components, it was necessary to find a way of converting this information into coordinates that could be reached by the cobot, which, with the air desolder and the support of the operator, would proceed with the disassembly operations. For this reason, the first task was to align the cobot with the support on which the board sits. This task, given the assumption of the repeatability of the operation, was done partially manually, defining a fixed position of the support on which the board is fixed and a default position on the robot. Once this was done, it was necessary to transform the processed image information into coordinates readable by the cobot. In order to do this, it was decided to discretize the space into two sections, one containing white pixels, and thus SMD components, the other black pixels and thus empty. The space was discretized by constraining the cobot to a movement of the end effector in a plane parallel to that of the board. The processed image is thus converted into a **nxm** matrix in which the matrix values are obtained by sliding a rectangle of variable size over the processed image that counts and reports the number of white pixels, i.e., the identified components, within the corresponding matrix.



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[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1329, 1353, 1236, 786, 270, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 552, 1233, 843, 639, 543, 378, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 327, 1065, 792, 537, 435, 348, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 588, 1356, 669, 420, 936, 339, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 654, 786, 456, 204, 360, 270, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 741, 933, 453, 147, 429, 261, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 756, 1083, 771, 330, 1062, 252, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 675, 651, 180, 276, 687, 261, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 522, 801, 228, 594, 468, 342, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 396, 774, 588, 396, 282, 435, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 414, 735, 630, 627, 108, 522, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 30, 870, 591, 393, 342, 279, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 462, 762, 555, 588, 297, 0, 0, 0, 0]
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 90, 216, 213, 183, 9, 0, 0, 0, 0]
```

Figure 10 – The matrix fed to the cobot

The information contained in the matrix will then be read by the cobot which, once aligned, will read the first value of the matrix, and proceed as follows:

1. If it reads '0' it will move to the right, i.e., the next value in the matrix, by a certain delta x;

2. If it reads a number greater than "0" it will stop to allow the operator to disassemble (approx. 15s per stop);

3. The operator helps the disassembly of the components with a spatula;

4. The operator presses 'enter' on the keyboard and the cobot resumes its routine;

The process is repeated by reading the values line by line from the matrix and the cobot can read several consecutive '0's at the same time to move smoothly to the first detected component. At the end of a line, the cobot automatically repositions itself on the line below and resumes the routine. The size of the rectangle that scans the image for the pixel count is a key parameter as this will determine the degree of discretisation of the space. A larger rectangle will perform a pixel count over a larger area of the image, which will correspond to a larger area of the actual board. Consideration should therefore be given to the size of the rectangle. In our case, we decided to choose by considering the size of the nozzle of the air desolder mounted on the cobot's end-effector. A smaller rectangle of the nozzle would increase the accuracy of detection but, in the case of densely populated boards, we would often find ourselves heating areas that had already been heated previously or with SMD components already removed. A larger area would instead decrease accuracy by limiting the percentage of removed components in favour of a faster procedure.

Figure 11 – Disassembly operation of SMD components

With this calibration, the procedure allows a complete disassembly of the board with times varying according to the size of the board and its population density. The system is not error-free, but the presence of the operator is also useful in the case of false positives. The operator can skip the cobot stop by pressing 'enter' in case of a false detection. The operator's task in this case is more limited to supervision except for helping with the removal of components. Removal is simple and is carried out with a small spatula and the support of gravity.

4.4. Learning Behaviour for THs Components

A different approach was used to separate the TH components from the board. From what emerged from the tests, the best solution was to uniformly heat the board to a temperature of 225°C and have the cobot remove the components using the GUI described in D5.1. The operator places the thermocouples on both sides of the board with adhesive tape, fixes the board on the preheating plate support by means of the special frame and while the board is being brought to temperature can perform the Learning Behaviour by guiding the robot over the components that it will then have to remove by means of the gripper of the end effector. The board in fact takes an average of 12 minutes to come up to temperature, allowing the operator to perform the Learning Behaviour with due care if necessary. Once the temperature is reached, the cobot will reach the saved positions, perform a grasping action by removing the component by placing it inside a container and then continue its routine. Although the system requires limited operator interaction, it should be noted that the learning procedure can be complex in this application. The components on which the cobot is placed are larger than SMDs but still small. Moreover, they have highly variable shapes and sizes, making careful manual positioning necessary if one wants to avoid constantly changing the shape of the hand-effector's fingers. In the case of incorrect positioning, errors may in fact arise during the automatic removal of components. Another source of error can be due to incorrect thermocouple positioning; an incorrect temperature reading could cause the removal procedure to start without the components having been desoldered, damaging the components and the board. Nevertheless, considering that the learning procedure is only to be carried out when changing the board type, we do not assume excessive setup by the operator.

5. Second Plant Configuration

5.1. Criticalities of First Configuration

Although sources of error can be mitigated by the presence of the operator, the first configuration of the board is critical in terms of disassembly time. The two steps combined take approximately twenty minutes for a total disassembly of the board. In the case of the removal of the TH components, the time is related to the method of heating the board, which for the reasons discussed in section 2 cannot be too fast to coexist with the operator. In the case of SMD removal, on the other hand, the procedure is fast, but since it is necessary to carry out numerous positions to completely disassemble the board, the entire disassembly process is slow. Later, we will discuss how this SMD removal procedure is nevertheless a good starting point for approaching an optimal solution. The first configuration thus allows a semi-automated total disassembly of PCBs to work, but which could hardly be implemented on an industrial scale due to the low throughput of processed material. In this section, we will discuss a second configuration of the system, which is simpler but at the same time more robust and quicker, allowing complete disassembly of the board.

5.2. Proposed Solution

The development of this second configuration required an extensive analysis of the trade-offs reported by the previously tested disassembly techniques. Bearing in mind that one of the key points in making the disassembly process implementable on an industrial scale is the throughput of processed material, the most important parameter considered in this analysis is the time required for a complete disassembly operation. By considering complete disassembly, we can assume that we are in a worst-case-scenario in which selective disassembly is not required, and thus calculate the time in a non-conservative manner. It was therefore necessary to simplify the approach to get some excessively time-consuming procedures out of the loop at this stage of system configuration. The proposed learning procedure of D5.1, although it proved to be a flexible tool in the hands of an experienced operator, presents some difficulties for a novice operator. Errors in the positioning of the end-effector can occur frequently in the case of inaccurate positioning. In addition, the two-step procedure of the first setup allows only one type of component to be handled at a time, inevitably slowing down the disassembly process. Disassembly tests also showed that the temperature reached by the board to remove TH components is largely sufficient to allow disassembly of the SMD components during the same heat treatment. This led us to consider a single-stage procedure in which both components are disassembled during the same heat treatment, reducing the time required to completely disassemble the boards. The interaction of the cobot in the disassembly process was limited, making more use of the operator's flexibility, thus making the process simpler and more user-friendly. The steps of the procedure are outlined below:

1. The operator places the board on the modified frame
2. Starts warming up the board by waiting approx. ten minutes
3. The operator removes the TH components with the help of the tongs and places them in a suitable container
4. The operator removes the SMD components with a sharp-edged tool slid across the surface of the board
5. The cobot assists in the recovery of the hot SMD components and places them in an appropriate container
6. The operator uses thermal gloves to turn the board and secure it to the chassis
7. The operator performs step 4 again

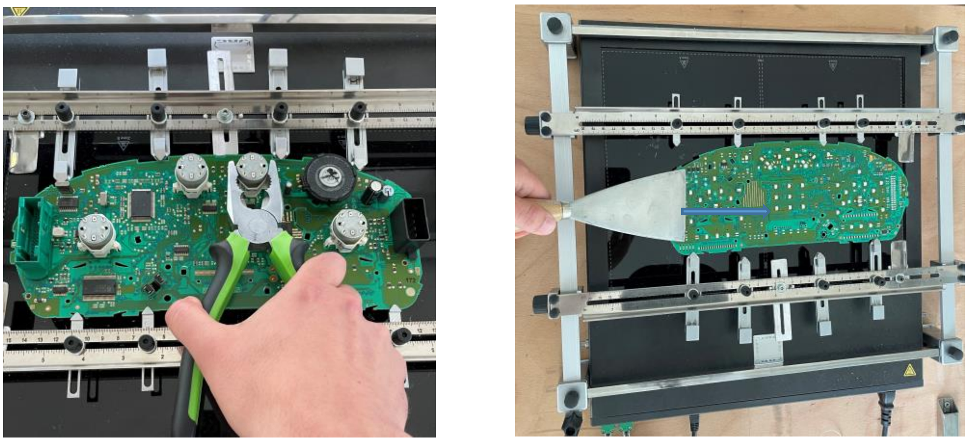

Figure 12 – Disassembly operation of SMD components

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The decision to use the operator to remove the TH components is because the removal may sometimes require some adjustment in terms of force and grip on the component. This is due to the possible inhomogeneity in temperature distribution within the board. The proposed procedure is effective for complete disassembly as it is more operator-controlled, more robust, and easier to implement. For the boards under consideration, the procedure has a duration of 12 min as shown in the Excel file in the appendix. Although in terms of performance this procedure marks a step forward compared to the previous solution, the material throughput is still too low to be a solution applicable on an industrial scale. Furthermore, sorting the components remains an additional operation to be performed after disassembly, requiring additional time to arrive at a material-based separation of the components.

6. Next Steps

6.1. Preliminary Profitability Analysis

Although the implemented solutions contain numerous interesting technological approaches for the disassembly of circuit boards, the critical point always remains the throughput of processed material. Since the masses of the individual disassembled components are a very small percentage of the mass of the entire board, it is essential that an optimal solution can maximize the volume of the processed boards. The materials contained in the boards also have different percentages depending on the characteristics of the board under consideration. If we consider the specific case of electronic boards from the automotive sector, it is difficult to think of a possible achievement of sufficient material volumes in the foreseeable future; in fact, most of the vehicles to be recycled are often obsolete vehicles with an average life of around fifteen years and which do not have many electronic components. Although this is a purely quantitative observation, since as mentioned in the introduction a systematic access of information is not allowed, it is safe to assume that the scenario might change when it is more modern vehicles that will be recycled since electronics on cars are continuously increasing. Considering the scenario of consumer electronics and the resulting volumes of WEEE produced the scenario changes dramatically. "Secondary CRMs supply to mitigate supply bottlenecks is therefore very limited and increasing CRM recycling rates is essential if growing demand is to be met. Waste EEE (WEEE or e-waste) is the largest and fastest growing waste stream on the planet (~50 Mt/yr, 3- 5% growth/year), and an important reserve of secondary CRMs for circular economy and reusable products/components that contain them. Secondly (Charles, R. G., Douglas, P., Dowling, M., Liversage, G., & Davies, M. L. 2020) highlights how WEEE volumes are growing rapidly and steadily with technological progress and how they can fully fuel the disassembly processes required to recover the CRMs responsible for supply bottlenecks. As for an estimate of the expendable capital to set up the plant, it is difficult to quantify it precisely. The profitability of the plant is in fact closely linked to the possibility of having specific recycling processes for the different materials contained in the components to be disassembled and to the type of boards processed. This is why we are actively collaborating with UnivAq to select and supply components on which to perform recycling tests on the pilot plant set up in the context of the FENIX and TREASURE European projects. Few studies exist in the literature regarding this type of investment; among them we can mention (Ramon, H., Peeters, J. R., Sterkens, W., Duflou, J. R., Kellens, K., & Dewulf, W. 2020) who in an attempt to realise a profitable process of tantalum recovery from electronic boards states that: "Based on the assumed and measured values, an internal rate of return on investment in a four-year time horizon and a minimum acceptable rate of return (MARR) of 15% corresponds to a permissible investment of €60,000". This calculation was made considering the price of tantalum and a single component removal time of 2.5s. This article also points out that it is essential to work at full capacity and in fully automatic mode to achieve reasonable margins. With this preliminary information and as previously mentioned in Section 2, the disassembly solution will have to be flexible and guarantee a consistent throughput of processed material. By being able to perform targeted disassembly operations, it will be possible to recover more different materials and increase the resulting profit in a case such as the one reported where the focus was only on components containing tantalum.

6.2. Proposed Optimal Solution

Following all the issues discussed earlier in this deliverable, a proposal for an optimal solution capable of processing a generic board and separating the components containing the CRMs as well as, if necessary, recovering the components intact will now be given below. A must-have feature will be the possibility to categorize components using AI to be able to proceed with a targeted disassembly of the components to be separated. The use of AI will make it possible to bridge the information gap, greatly increasing the flexibility of the solution. As can be seen from D3.3, complete disassembly of boards is not always necessary, as some components can be recovered even if they are recycled together with the board. Being able to select only the critical components by means of a classifier would therefore allow disassembling only certain components, reducing the time needed to work on the individual board. and separating the downstream recycling streams to increase the recovery rate of the materials in these components. We are currently evaluating the best way to implement such a solution; we are trying to collaborate with the CIRCUITS project to acquire a sufficiently detailed dataset for model training. It is also fair to report that the AI sector is constantly growing, and numerous open-source tools are frequently released. Among them, the very recent Meta's SAM (Kirillov, A., Mintun, E., Ravi, N., Mao, H., Rolland, C., Gustafson, L., Xiao, T., Whitehead, S., Berg, A. C., Lo, W.-Y., Dollár, P., & Girshick, R. 2023) could solve some of the critical issues reported in section 2 of this deliverable. The tool is open source, can be imported as a Python library and allows any type of object in an image to be segmented very precisely. This, as can be seen in image x, allows the board to be segmented at the component level, solving one of the problems associated with the positioning of anchors in this type of application where the small size of components is a major problem.

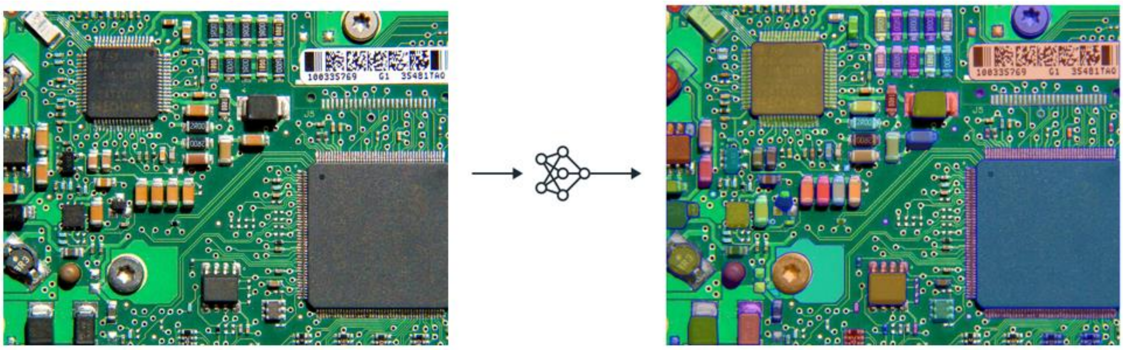

Figure 13 – SAM testing on a random PCB image

By having an efficient segmentation system, the images can be passed to a classifier capable of recognizing the components containing the desired CRMs. Having reconstructed the information of the class of components, we can then also obtain information on the coordinates of the components, coordinates that can be communicated to an actuator, in our case the cobot, to carry out disassembly operations. Another fundamental problem with the previously presented solutions was the time required to bring the board up to temperature. The component classifier can only provide real added value if the components are removed in a time-saving manner. Furthermore, by using non-destructive physical component removal systems, it would be possible to recover intact and functioning components from the board. This possibility would represent a further possibility of interest from an industrial point of view by enabling recovery. Although going into further details of this possibility is probably beyond the scope of this deliverable, since this topic will be dealt with extensively in the CIRCUITS project, it is permissible to quote again (Ramon, H., Peeters, J. R., Sterkens, W., Duflou, J. R., Kellens, K., & Dewulf, W. 2020) to provide an idea of the possibility of this scenario: "The average life of a PCB is 20,000 hours, just 5% of the designed lifespan of its components. At EoL, many components are functional and potentially reusable multiple times." The air desolderer, although allowing disassembly in about 12s per SMD components, did not prove to be the most efficient tool. The use of heat-sinks could increase efficiency, but since the flow of hot air points directly at the component, the safety of the component is not guaranteed. By analysing the products available on the market, we were able to identify some state-of-the-art rework tools that allow precise and optimized disassembly operations. For the removal of SMD components, a modular thermal climper is the best solution, guaranteeing fast removal and preserving the integrity of the removed component. For the removal of TH components, a desoldering iron tool is optimal, capable of quickly removing the solder material from the component pins, greatly reducing the time required to perform the disassembly operation. As far as an automatic implementation is concerned, it will be necessary to construct suitable tool-holders capable of being assembled and controlled by the cobot. A system with the given characteristics will be flexible and efficient enough to be able to process not only automotive boards, but a vast number of different PCBs by enabling downstream recycling processes to increase the recovery rates of the various materials. If we consider what the techno-economic analysis of (Ramon, H., Peeters, J. R., Sterkens, W., Duflou, J. R., Kellens, K., & Dewulf, W. 2020) reported earlier, it only considered the recovery of Tantalum capacitors. Therefore, if it is considered that with the proposed system, most of the CRMs on the board will be recovered, the margins will be much greater than reported, allowing the use of semi-automated solutions.

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8. Appendix

In the firs table of the appendix are reported the mass balances after the disassembly operations along with the parameter used to carry out the disassembly operation. It is important to mention that this data is not coming from the pilot plant. Most of the disassembly operation here reported were performed to retrieve additional data on PCB composition in terms of components.

PCB	Tot mass (g)	Board mass (g)	TH mass (g)	SMD Mass (g)	Frame Config.	TC up (°C)	TC down (°C)	Effort or criticalities	Lead Losses (g)	Dis. time
2nd GEN	151.33	82.66	64.16	3.78	Low	250	217	green port	0.73	11 min
1st GEN	178.20	80.00	85.00	12.39	Low	250	217	no	0.81	11 min
3rd GEN	147.49	99.05	39.04	9.09	Low	250	217	no	0.3	11 min
LCD AF 81	147.93	65.62	15.51	63.92	Low	250	217	metallic comp.	2.88	14 min
LCD AF 80	12.66	6.77	4.19	1.5	Low	250	217	through hole comp.	0.2	11 min
VOLVO	94.83	92.85	//	1.26	Low	250	217	no	0.7	8 min

In the below charts are instead reported the component composition of each board trying to identify the different components present on the board. The values are expressed in grams and, working with small components some mis-classification errors are considered.

PCB	Ta Capacitor	LEDs	Resistor	Oscillator	Ceramic Capacitor	Electrolytic Capacitor	Cylindrical Resistor	Inductor	ICs	Transistor
2nd GEN	//	2.14	0.63	//	0.06	//	//	//	0.89	0.02
1st GEN	0.34	1.75	0.63	0.69	0.30	//	0.47	0.28	3.86	0.06
3rd GEN	0.23	1.51	0.94	0.74	0.71	1.29	0.12	0.15	2.37	0.68
LCD AF 81	//	0.32	0.56	//	5.01	//	//	40.79	1.70	0.02
LCD AF 80	//	//	0.22	//	0.54	//	//	//	0.66	<0.01
VOLVO FELX	//	1.17	//	//	0.10	//	//	//	0.02	//

PCB	Unknown	Zener Diode	Array Capacitor	SMD filter	Reg Tens	Mosfet	Mega Mos Res	Potentiometer
2nd GEN	//	//	//	//	//	//	//	//
1st GEN	0.18	0.32	0.31	0.09	0.10	1.51	1.08	//
3rd GEN	0.12	0.14	0.12	//	//	//	//	//
LCD AF 81	0.51	0.71	//	//	//	12.49	//	0.71
LCD AF 80	0.8	//	//	//	//	//	//	//
VOLVO FELX	//	//	//	//	//	//	//	//