Technological implementation of pilots

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Abstract

This report D4.1 describes the status of the implementation of the pilots in the CIRC-UITS project after two years. Chapter one serves as an introduction to the WP, describes collaboration of Pilot partners with the different work packages and looks at the risk analysis that was defined in the beginning of the project.

The four pilots are each described in their own chapters (2-5). Each of these pilots describes the as-is scenario (now 'was') before the start of the project, the expected outcome for the project and defined validation targets, the activities that have been performed so far and how those activities have contributed to reaching the targets, the innovative aspects of the work performed and plans for the next phase of the project.

Chapter 2 describes the status of Pilot 1, an Electronic Stability Program (ESP) including eco-design process, led by BOSCH (ESP use case). In this pilot data analysis was performed to evaluate the status quo of the ESP; data analysis is done by OFFIS, Maras and SUPSI. Furthermore, first try outs were performed with recycling, reusing and repairing. Chapter 3 describes Pilot 2 about the eco design of a tire pressure monitoring sensor (TPMS), led by CONTINENTAL (TPMS use case). Two concepts were defined, and several circular aspects of these concepts were investigated and are discussed. Currently a favoured concept has been chosen for further analysis. Chapter 4 deals with the work done in Pilot 3 on green in-mould electronics for the automotive industry, led by TNO (IME use case). Several technological advancements are discussed, including the first ever re-moulding of disassembled IME devices. Also, an LCA on repair demonstrates the potential of these technologies. Lastly, in chapter 5 the pilot led by ERION on a sorting process for printed circuit boards (PCB use case). A lot of work was performed in this pilot with respect to choosing and collecting suitable boards. It demonstrates the difficulty the industry faces, the importance of this work and the need for digital tools.

In chapter 6 a pilot overarching activity is described which is led by POLIMI together with all pilot partners. This additional work was defined during the project and has seen considerable developments. We describe remanufacturing of PCBs and printed foils and the utilization of digital tools for it. Since it has many similarities between the different pilot implementations the work is presented as one chapter.

Finally, in chapter 7 the status of implementation of digital tools for the pilots will be described. Together with partners from work packages 2 and 3 considerable effort has been poured into defining the needs and requirements for digital tools and assessments for each pilot. While full results of implementation of these tools and methodologies will be presented in a later deliverable, summaries of the various methods and some initial implementations are already presented here.

CIRC-UITS

List of acronyms

AI	Artificial Intelligence
ATE	Automated Test Equipment
BAT	Best available Technique
BGA	Ball Grid Array
BoL	Beginning of Life
BOM	Bill of Material
CAD	Computer aided design
CAS	Chemical Abstracts Service
CE	Circular Economy
COBOT	Collaborative robot
CRM	Critical raw material
CV	Computer Vision
CWA	CEN Workshop Agreement
DfR	Design for recycling
DT	Digital twin
ECU	Electronic Control Unit
ECI	Energy Circularity Indicator
ELV	End of life vehicles
EoL	End of life
ESP	Electronic Stability Program
FR4	Flame retardant 4
FW	Firmware
GUI	Graphical User Interface
GWP	Global warming potential
HMI	Human-Machine Interfaces
IC	Integrated circuit
IJM	Injection mould
IMDS	International Material Data System
IME	In-Mould Electronics
KPI	Key performance indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHA	Large Household Appliances
MCI	Material Circularity Indicator
MQI	Material Quality Indicator
OEM	Original Equipment manufacturer
PC	Polycarbonate
PCB	Printed Circuit Board
PCI	Product Circularity Indicator
PRO	Producer Responsibility Organisation

PCF	Product Carbon Footprint
PTH	Plated through holes
QFP	Quad Flat Pack
SLCA	Social Life Cycle Assessment
SMD	Surface mounted device
SOTA	State-of-the-art
SW	Software
TPMS	Tire Pressure Monitoring Sensor
TRL	Technology Readiness Level
WEEE	Waste from Electrical and Electronic Equipment
WMcode	Washing machine

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1 Introduction

1.1 Overview

D4.1 describes the status of the implementation of the pilots. These involve technical developments to improve sustainability aspects in their respective fields and products and the simultaneous implementation of digital tools in collaboration with the partners from other WPs. The work described until now has been performed over the past two years, as the start date of WP4 was preponed from M12 to M1. As a result, the planned effort for D4.1 was spread from 1 year to 2 years. Since no additional deliverables were defined this report is the first deliverable from WP4. The concept goals and targets of the pilots, which were partially defined in collaboration with other WPs during the project, will be (re-)discussed. Then the technological advancements and application of digital tools under development are demonstrated.

1.2 Collaboration with other WP's

WP4 is an important pivot in the project, where work from all partners converges. First of all, the pilot leaders are each developing new innovative technology and products to enhance sustainability within their respective fields. These pilot use cases are supported by the digital tools being developed in WP2, WP3 and WP5. At the same time, while benefitting from these tools and the partners developing them, the pilots also function as test cases for the tools, enabling partners to validate, refine, and potentially improve these digital tools. This collaborative approach benefits both the pilots and the tool development work packages, creating a mutually supportive workflow. Furthermore, from the beginning of the project the industrial pilots have been discussed in great detail with partners from WP1 for deliverable D1.4 and then again for deliverable D1.5. Together, the scenarios have been refined and elaborated, which resulted in updated and concise descriptions of the current scenario, planned activities, expected impact and suitable validation targets for each pilot. These descriptions set the stage for the work performed in the pilots and are utilized again in this deliverable (descriptions X.1 'Initial state of pilot', X.2 'Expected outcome' and x.3 'defined targets'). Furthermore, these validation targets set the bar to which we can now measure the status of implementation.

1.3 Updated Risk overview

Risk 1: Requirements incomplete or not detailed enough because of confidentiality issues or low involvement of application partners.

Update: Having extra time by starting in year one instead of year two has helped the WP4 partners to get the requirements in order. Furthermore, working together and having workshops for the deliverables in WP1 helped meet the requirements. Confidentiality has not been an issue so far. All industrial pilot partners have been willing to share and are complimented for that.

Risk 3: The most relevant risks within LCA-LCC analysis are lack of data availability both for the CIRC-UITS pilots and for the current state-of-the-art practices.

Update: it is a challenge for some of the pilots. Not all pilot partners are experienced with LCA & LCC and have had difficulties understanding the data requirements for those analysis. However, the partners from WP3 have been helpful in guiding the pilot partners in delivering the required data. Lately more discussions have been taking place on this topic and data sharing is going well. The risk is at least under control now.

Risk 8: Covid restrictions.

Update: No longer relevant.

Risk 10: Delay in meeting the delivery deadlines, poor quality of deliverables and failing to meet the measurable objectives.

Update: The work performed by the pilot partners has been frequently discussed in various of the consortium, WP, topics, GA and pilot meetings. There are no indications that there is a serious slack in quality or progress towards the defined objectives. For the deliverables there is always a quality control mechanism in place.

Risk 11: Conflicts in the consortium.

Update: There have been no major conflicts in WP4 and there is no indication this might occur.

Risk 12: Co-ordination and leadership missing.

Update: There have been a few months period with a lack of WP4 meetings due to limited necessity from the different pilots. Towards the deliverable the meetings have continued again to guarantee the required collaboration for finishing the deliverable and the collaboration with the other WPs.

Risk 13: Planned resources are not enough to achieve the project goals.

Update: Following the midway financial overviews most budgets are on track. Also following the midway review meeting in Brussels, the developments were considered on track. So far there seems to be a match between targets and budget.

Risk 14: The expectation of partners concerning the exploitation is not met.

Update: No status update.

Risk 15: End-users do not accept the developed methodology and the associated technical solution.

Update: In WP4 all pilots have end-users as part of the members. This ensures the solutions are in line with the requirements of the end-users. With other WPs there is frequent discussion and analyses, methodology and other digital tools are developed with the goal to be suited for the various end-users. This seems to have gone quite well so far.

Risk 16: The integration of recycled/reused products in production/assembly lines is not practically feasible.

Update: This risk will be re-evaluated towards the end of the product.

2 Pilot 1: Electronic Control Unit

2.1 Initial state of the pilot

The aim of this pilot is to advance the eco-design of an Electronic Control Unit (ECU), which is used for the management of the Electronic Stability Program (ESP). The ESP makes a significant contribution to road safety by preventing vehicles from skidding, thus helping to prevent accidents and save lives. Vehicle manufacturers strive for personalization and differentiation, for example through driving dynamics and driving experience. This kind of product is mounted millionfold in cars all over the world. Remanufacturing and repair of used ESP devices for dedicated customers has already been established since some years at BOSCH in low volumes. To avoid cost increases due to low volume in the aftermarket or missing spare parts due to supply issues (e.g., chip crisis), BOSCH decided to focus on ECUs.

ESP units, like many others car electronics components, have been always designed with focus on their functionality and restrictive legislative requirements. Therefore, sustainability and circularity aspects have not been considered as relevant until now. Also, from the End of Life (EoL) perspective the correct management of obsolete car electronics has never been a priority. Given the absence of both a dedicated European/national regulation imposing its extraction from End-of-Life Vehicles (ELVs) and a dedicated market for obsolete car electronics components (and related secondary materials), none of the actors involved in ELV management practices do that spontaneously. The general view of the interviewed actors on this topic is that this is a not profitable procedure. Hence, these components are not disassembled from ELVs, finishing to be shredded together with the rest of the car. This behaviour has been already identified as a big economic loss for the entire automotive value chain both in terms of lost profits for dismantlers/shredders/materials recovery plants and lost volumes of secondary materials/spare parts that could have been re-introduced either in the automotive or related value chains. This issue makes also evident the low circularity level of the automotive sector in terms of critical materials recovery from car electronics. Again, all these wasted materials (especially precious and critical ones) have a high negative impact in terms of natural resources depletion (particularly important at political level). Finally, considering the current semiconductor crisis in the automotive sector, the incorrect management of car electronics components sounds like a big paradox. Considering all these aspects together, there is an urgent need for adopting new eco-design logics in order to ease both the disassembly, repair and recycling of ESP units, in order to make their EoL management a profitable business.

2.2 Expected outcome

The kind of one-way development (linear economy) that was the focus for many years in the automotive electronic business needs to be changed. For mechanical components there is partly circularity in the way that recycled materials are used but even there the manufacturer does not know much about the material itself. CIRC-UITS can help to understand better what obstacles prevent to ensure the quality and the lifetime for products with recycled material. Electronic parts have a significant impact on the CO2 footprint, and it is no longer acceptable that they are not repaired, recycled, and reused in a reasonable and structured way. The reasons are effort, time, costs, and possibilities. To build a digital twin of such an electronic and bring them in circularity will give the manufacturer the opportunity to learn how to create the electronic in a way that circularity becomes economical. This is the idea also for the ESP use case. To learn more about the product, the obstacles and failures toward the development of a sustainable product (e.g., a product that can be repaired, reused and recycled) must be assessed through a set of sustainability indicators (KPIs). At the end, the ESP use case will get its own sustainability passport. The main objectives of the ESP use case are as follows:

- Extend use phase (repairability): change the product design to allow better disassembly and reassembly, and for better access to surface mounted parts on the PCB (back and topside level).
- End of life (recyclability): change the product design of housing and PCB for better dismantling. (In best case with standard tooling of dismantler and workshops).
- Manufacturing (material replacements): identify possibilities to replace material by recycled material in the product and find possibilities to lower manufacture energy by use of new materials.

One of the main intents of CIRC-UITS is trying to increase the awareness of the different actors involved in automotive value chains about the value embedded in car electronics components and the importance of their correct recovery. To this aim, the ESP use case will be focusing on both Beginning of Life (BoL) and EoL processes and I4.0 technology to increase the circularity performance of ESP units.

2.3 Defined targets

Since the demand for an ecofriendly product has increased in the last years, BOSCH product marketing forwards this change to the product designers. A decision helping dashboard to point out more than costs and to support shift of balance towards better sustainable properties is the main driver of participation of BOSCH in the CIR-CUITs project.

In collaboration with the project partners OFFIS, SUPSI, MARAS, ERION, ALPHA and POLIMI the goal is to figure out how design decisions for repair, recycle and reuse works for a superior target of an overall CO2 reduction by 15% in using our ESP product. In supporting better recycling of products, it is consequently necessary to insert recycled material into new products. Target is here 20%.

It is important to differentiate between Product Carbon Footprint (PCF) and Life Cycle Assessment (LCA). PCF refers only to manufacturing the product, LCA also includes the whole product lifetime (use phase until end-life). To that end, using new more sustainable materials to reduce the PCF during manufacturing completes the sustainable strategy of pilot 1 (Figure 1).

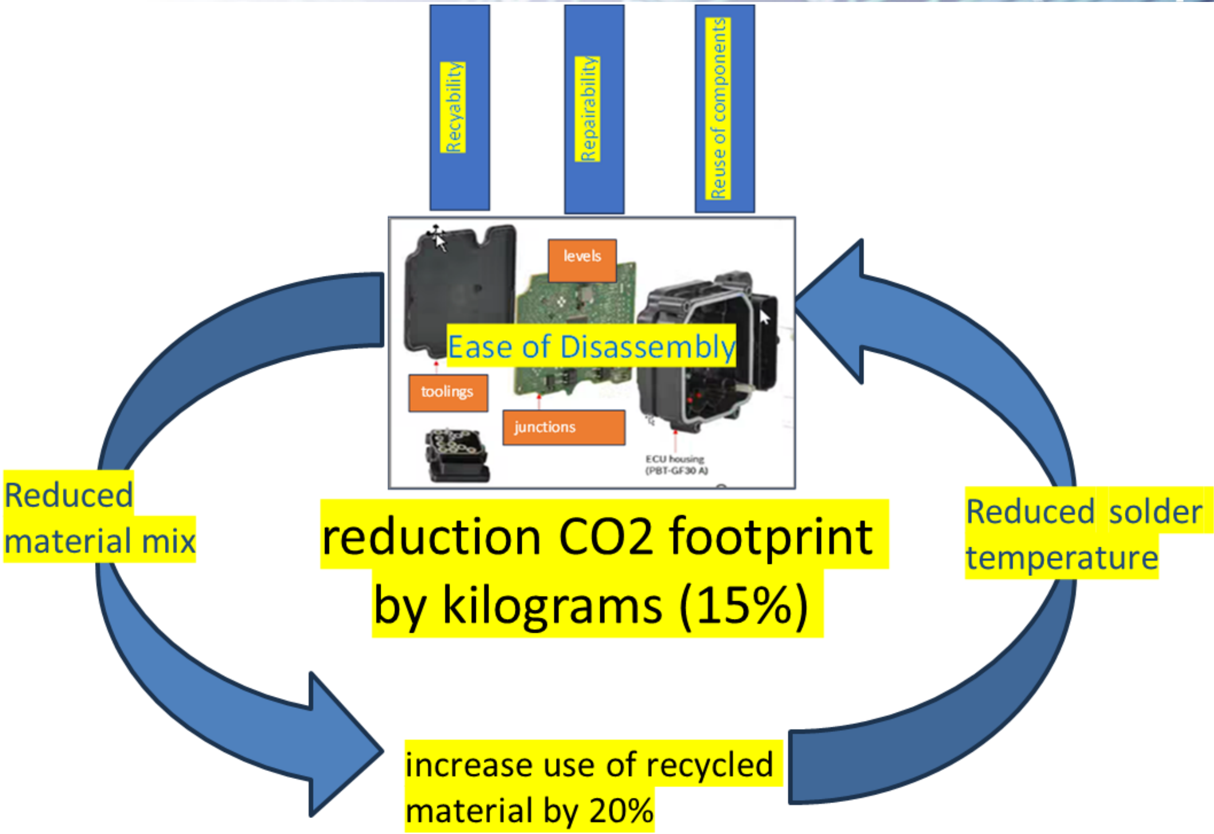


Figure 1: Ease of Disassembly is the basis for many sustainable pillars. All-encompassing target is CO2 reduction.

2.4 Performed activities and current state of targets

All activities are performed in collaboration with the project partners (see Figure 2). Important first steps; to get to know the status of the product and the highest potential of improvement (hot spot analysis). Maras and SUPSI provide data about exergy and CO_2 for the current available ESP. This together with the critical raw material information's, provided by Offis, will give the starting point of the digital passport and the digital twin. Also, with this information the design and material optimization can be done. POLIMI supports the efficiency of the repair by their activities about automatic disassembling (see chapter 6). With DIN (and other partners) KPIs of repair are evaluated and described (see chapter 2.5). For BESUs serious games we work together by providing facts and information and having discussions, as well as the roles of engineers and scientific people. Innovative solder pastes by ALPHA will be included in the new design update coming in a later stage.

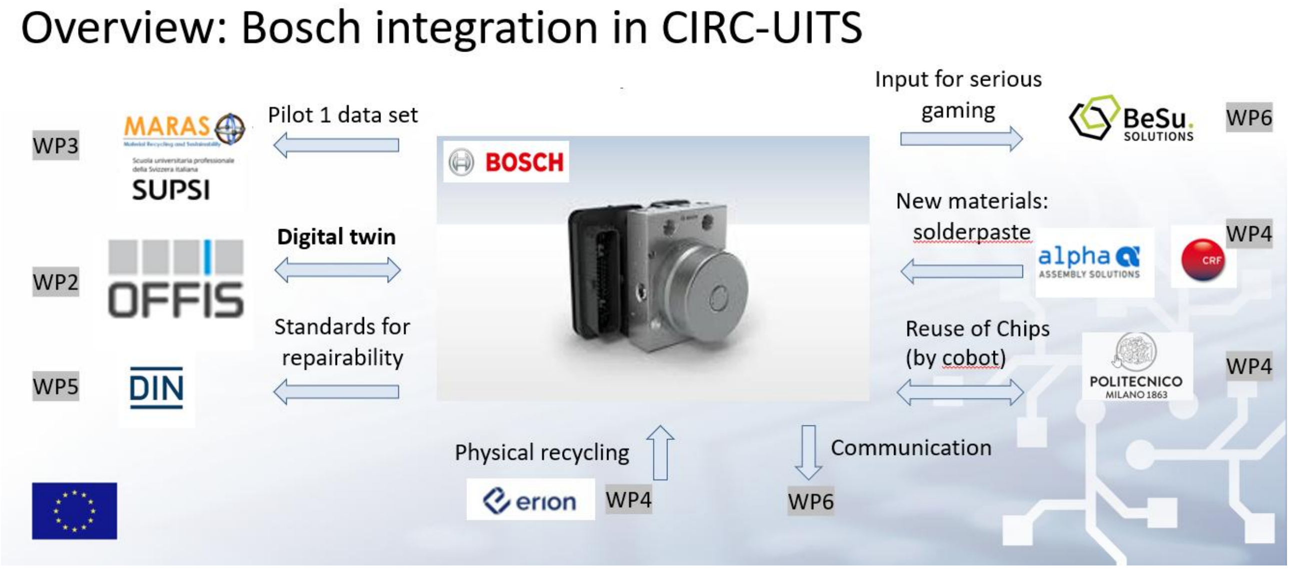


Figure 2: Interaction of Pilot 1 with the partners and the work packages (WP).

2.4.1 Analysis of status quo

To implement and evaluate the status quo of the ESP, data analysis is done by Offis, Maras and SUPSI. The base of Pilot1 data is the Bill of Materials (BoM) combined with IMDS (International Material Data System) data of the subcomponents. It is a complete list of the raw materials and components. Process and production data was added to make the result more precise. Those are mainly energy data, for example: energy for machines, cooling, heating, environment, storage. This combination results in a complete dataset. The dataset is now utilized with the various tools under development by MARAS (for exergy value and recycling), OFFIS (for critical raw materials), and SUPSI (GRETA tool for CO_2 Footprint and environmental data). The SUPSI data will be available by the end of January, thus for the results in this deliverable Bosch internal CO_2 values are used. The flow of data is also schematically described in Figure 3.

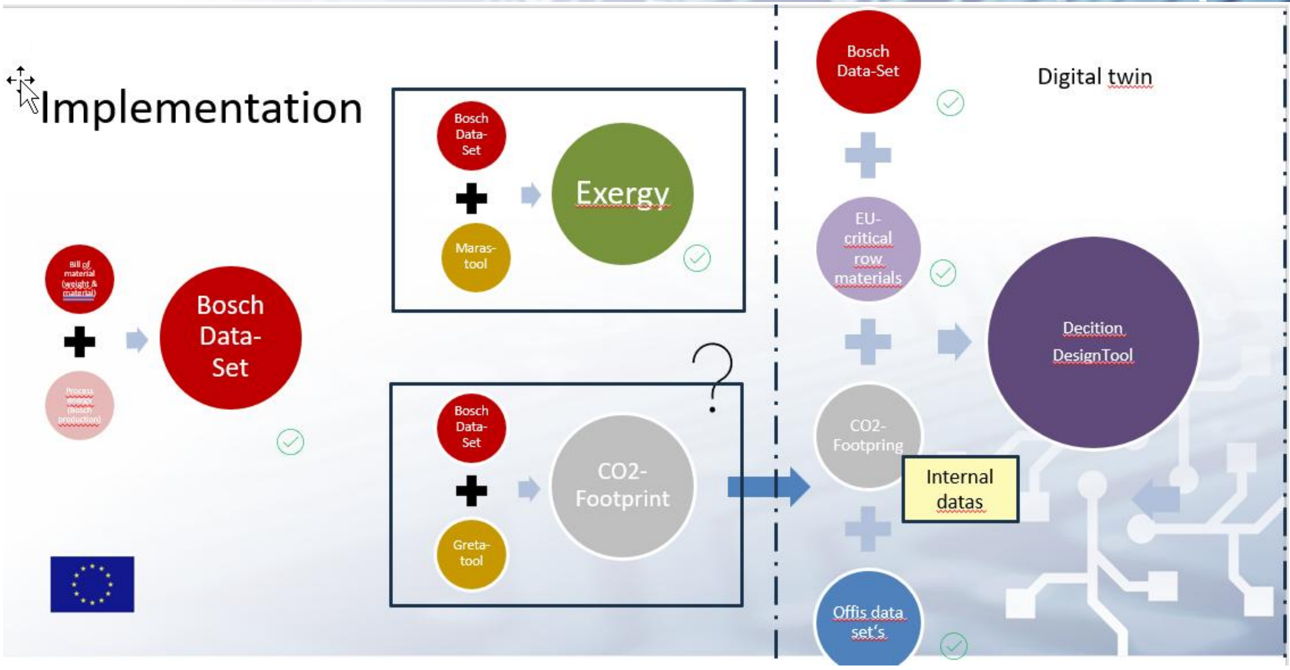


Figure 3: schematic implementation of pilot 1 to the data system.

Important is that all output data refers to the whole ESP, as well as to subsystems and finally to subcomponent level. Those subcomponents are described in Figure 4. For the assembled PCB three main components are selected as a starting point for calculation. Due to the high number of components on a PCB it was not possible to calculate all of them. The housing and the solenoids are fully implemented.

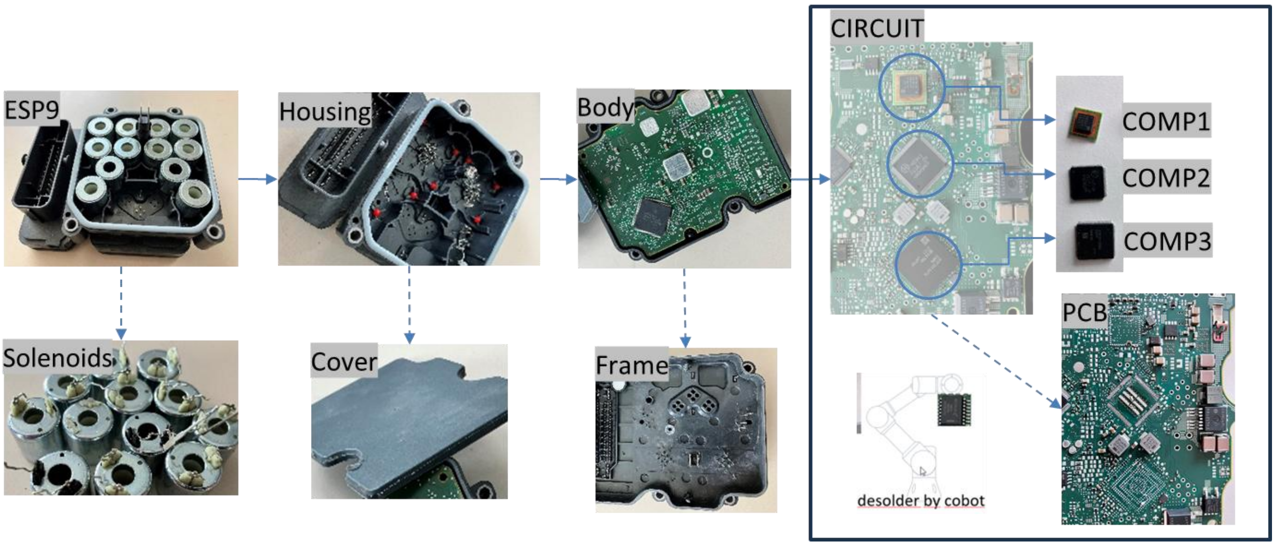


Figure 4: ESP and subcomponents that are relevant for sustainable evaluation.

The first dataset results contain ESP, subcomponents and component and are shown in Figure 5. The whole part of an ESP9 weighs 500g. Solenoids describes the twelve disassembled big copper coils in the system. Housing means everything without the solenoids. Body means the circuits and frame without the cover.

Circuit itself is the sum of PCB and the three selected components. This systematic nomenclature is used for all distribution at pilot 1.

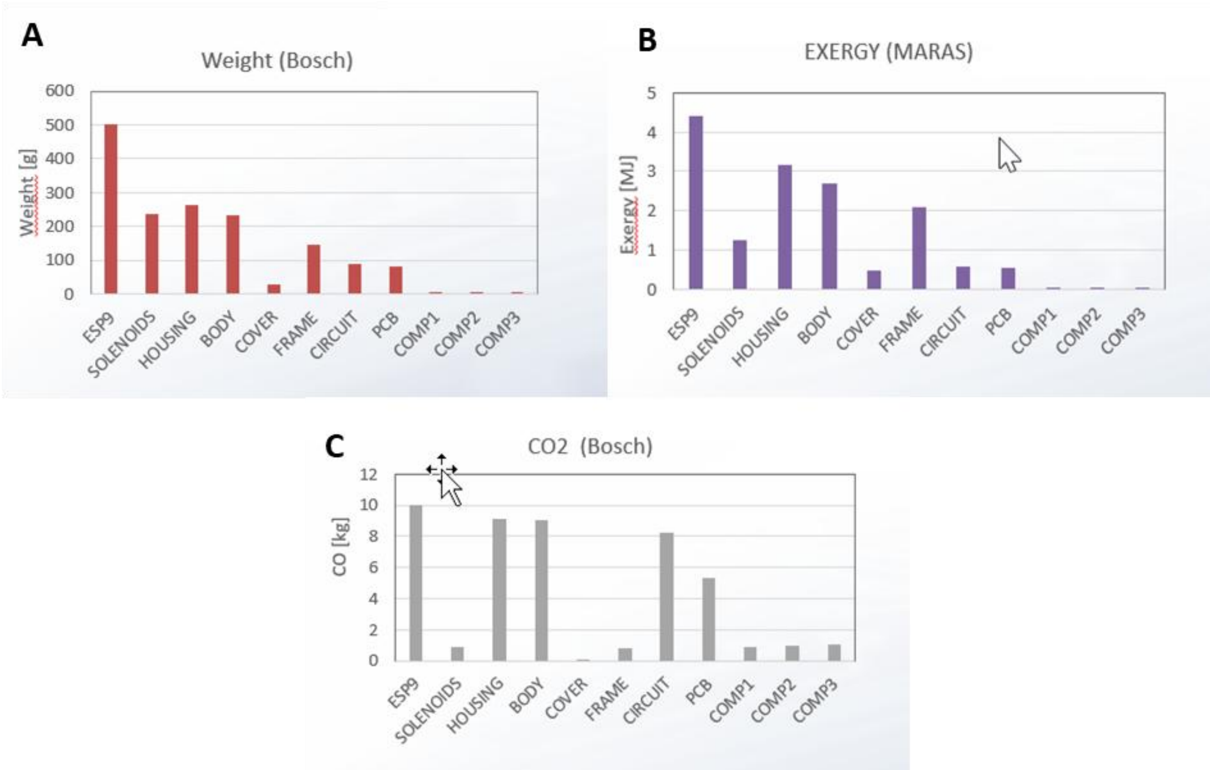


Figure 5: A. Weight of the components and subcomponents. B. Exergy of components and subcomponents. C. CO2 number of components and subcomponents.

After evaluating the values, a breakdown to the system was done by putting the values relative to each other to reach a percentage value of each component comparing it to the whole system (Figure 6). This view allows us to compare the different methods and to see the impact and the contribution. With respect to weight the solenoids have the biggest contribution, because they contain steel and cooper. Exergy and organic materials are the most important to evaluate in the ESP. This includes the housing / body, the cover, and the organic part of the PCB. This high contribution is due to the long journey from oil to a polymer with a lot of lost energy. More information and a deeper evaluation can be found in section 7.2.1.3.

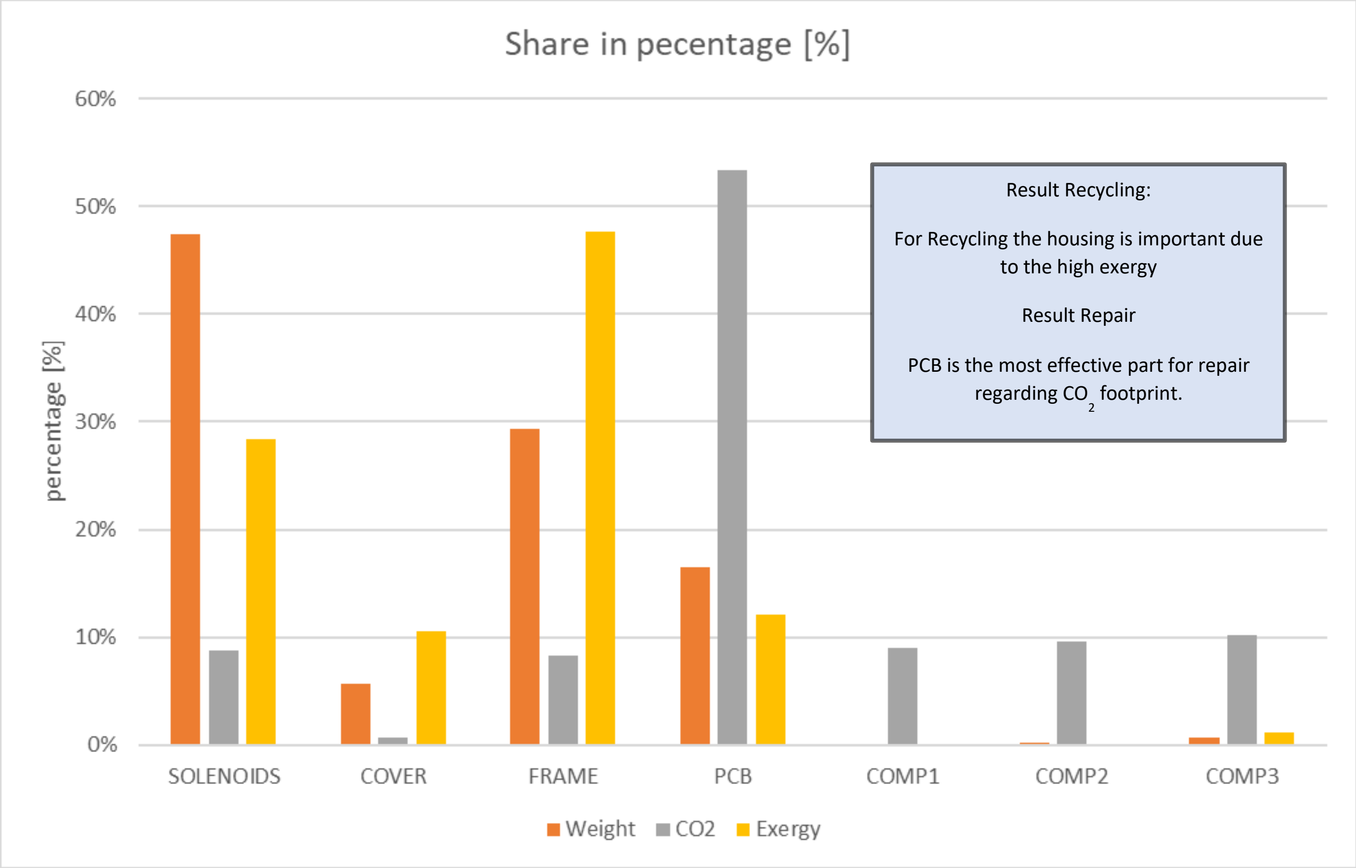


Figure 6: Comparison of subcomponents weight, exergy, CO2

2.4.2 Recycle and reuse try out

A product that can be easily dismantled supports already many recycling possibilities. The reason is that many materials can be already separated mechanically instead of melting the complete material mix and reaching a high loss of materials.

To find out more about our own product, the physical recycling of ESP devices was done with ERION, a Producer Responsibility Organisation (PRO). Several devices were shredded or manually disassembled (Figure 7). Due to the used connections / design elements in the product ERION recommended to remove the PCB and solenoids first manually before using shredding technologies. Separating organic from inorganic materials is also the main conclusion out of the exergy analysis from MARAS. This underlines that without separation mainly the organic parts are relevant and worth recycling. For ESP this is the housing and the cover.

Figure 7: Dismantle Trial by ERION.

In the same manner making subcomponents or even complete PCBs easier to be separated from the product can support the reuse of subcomponents. One serious case is for example to stock up on production with used parts due to a shortage of subcomponents. Most interesting for ESP are the highest integrated components (ICs). These parts relate to nearly 30% of the PCF. If it is possible to reuse the whole PCB including the ICs, you can keep up to 80% of the PCF. In cooperation with POLIMI (see chapter 6) these ICs were desoldered by COBOT to figure out potential business cases in the future. The recycling and reuse of subcomponents represents a not too high effort to the design of a product, as most of the used connections can be released non-destructively.

2.4.3 Repair try out

There are in general two main failure modes in the ESP that could be relevant for repair. One is physical damage to the outside of housing, connector or solenoids and on the other hand electrical components on PCB level or interconnections that can fail. In both cases two types of junctions in the system are involved. They are the main blocking points for the ease of disassembly of the existing ESP and most important connections in a more sustainable design.

- The cover is welded to the housing. Only by milling is it possible to open devices for repair. (see Figure 8). The used cover must be replaced by a new one. Due to the destructive opening procedure the housing is not even prepared for further welding of a new cover. Only glueing the cover to the housing would be possible. This will not fulfil the technical requirements in tightness and robustness.

Figure 8: Destructive disassemble of laser welded plastic junction between housing and Cover.

- At ESP, the press-fit technology connects the contact terminal and external solenoids with the main printed circuit board (PCB). The press fit pins have an elastic press-in zone with springs. The PCB is designed with plated through holes (PTH). When PCB is pressed into the press-fit pin during manufacturing, each pin is deformed by insertion. A permanent contact force is achieved that enables a reliable electrical and mechanical connection over lifetime. The tin plating in the ESP press-fit-pin-system supports additionally a cold-welded interconnection after the insertion between pin and plated through holes. With the welded interconnection an exceptionally low resistance and a high mechanical stability is achieved. The insertion process requires special tooling that ensures less strength for the PCB and for its soldered components. The tolerance of strength to PCB and components is strictly limited. The combination of spring force and welded interconnection increases the release force that is needed to press out the PCB again. Both involved surfaces of pin and holes burst during this release and are then not optimal prepared for further reconnection. By pressing the PCB back to the Press-Fit pins it is not ensured that the needed robustness is achieved. Further steps are necessary to stabilize the interconnection, for example with a soldering step.

To disassemble the PCB, you must apply a distributed force on the bottom side of the PCB. This is needed to keep local force low in PCB layers and solder joints. The design of our ESP makes it impossible to reach these points on the board without destroying the housing. Disassembling trials of the PCB from top level results in a too high force (see Figure 9). Resuming a repair of the existing product is possible but only when you replace housing, cover, and solenoids. The repair effort is very high with further soldering and the operation is complex due to handling the PCB from the bottom side of the device.

Figure 9: Destructive disassembly of press fit junction between PCB and Housing.

For both connection types there have already been reversible solutions in the market for many years. Often these connections do not match the technical requirements in the automotive industry. These requirements relate to safety and to the rough environment the ESP is working in. That can be the motor bay of a car or even under the car (see Figure 10).

Figure 10 Rough environment for a BOSCH ESP at the underbody of a vehicle.

In parallel it is mostly an economic decision by product designers and manufacturing plants to use a cheaper non-reversible connection in the product. These are only two reasons why repairability is still out of focus in the automotive electronics industry. To underline the focus, it is therefore beneficial to have one standardized indicator for repair. Making repairs comparable between different products can increase the pressure to manufactures by the need of the market. BOSCH and OFFIS applied the most promising norm provided by DIN (DIN45554) to the ESP. This work will be published by DIN. Briefly summarized:

- The norm DIN45554 is powerful but therefore also very complex and time-consuming;
- Most of the criteria in the norm are useful. Bosch indicates even some further criteria based on our experience in repairing products;
- At least we get an indicator that is highly influenced by the individual knowledge, mind set and accuracy of the user;
- The lifetime extension by the repair is missing in the indicator and so the success and quality of the repair is not visible in the end;
- The goal of one global indicator will be difficult to reach with this norm in Table 1.

Table 1: Lessons learned from DIN45554.

Use case	Users	Limitations
Comparison of two concepts with small changes (Pilot1)	product development	Concepts are rated by one user, identical datasets, models and weightings are available
Compare of two products of the same manufacturer	Product group development	Datasets may be the same when technology and architecture are not too different. Two different models, necessary. Weightings can be the same as the manufacturer is the same, comparison may work with exceptions
Compare different product on the market	product marketing, customers	No common dataset, weighting, models, available: no comparison possible

2.5 Innovative aspects compared to SOTA

Every manufacturer in the automotive industry has targets to reduce PCF. They are mainly focused on using less materials or replacements with less CO2 consuming materials. Taking further sustainable aspects like repair, recycling and reuse into account can be a booster for the next greener generation of electronics. Therefore pilot 1 focuses on these sustainability pillars and on the LCA of the product. Repairability is the most challenging pillar for such a complex electronic like ESP.

One innovative aspect is the definition of a repair indicator based on physical values like time and energy (see Figure 11).

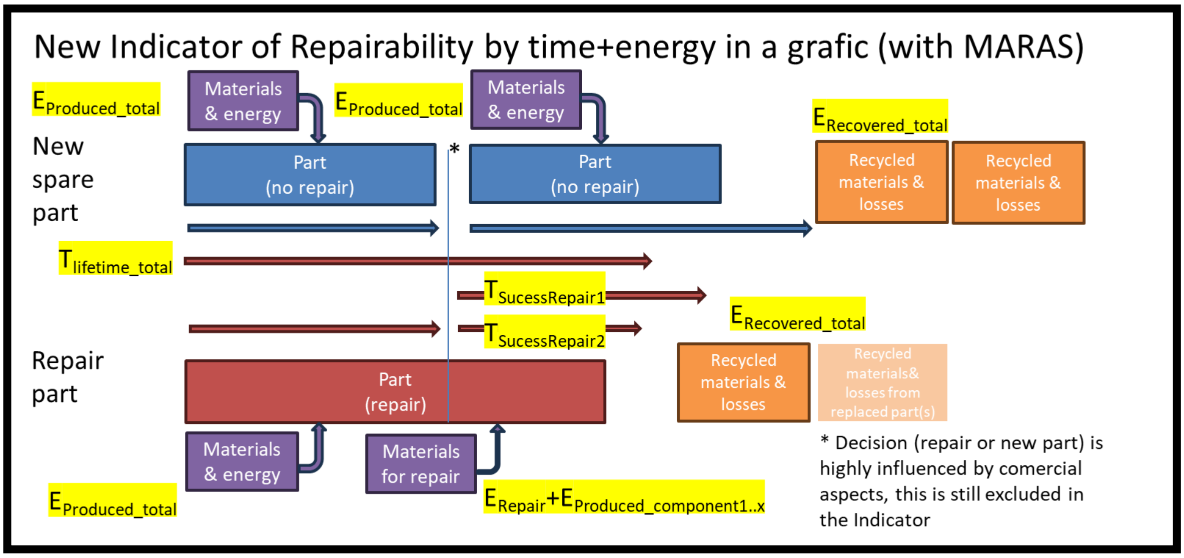


Figure 11: New repair indicator based on time + energy.

The outcome is an indictor resulting in the unit watthours. It involves:

- the manufacturing energy and exergy (by MARAS) of the product and of the involved subcomponents that should be repaired;
- the repair effort and success;
- the recovered energy due to recycling.

The basis of the indicator is the knowledge of how and which part of the product must be repaired. The indicator can then be displayed in a kind of heatmap when you take the original product as a reference. Also design changes are now visible on the map. See the arrow in Figure 12, it is equal to a design improvement regarding repairability at ESP.

Repair_Effort_relativ (kWh)		Repair_Success (Years)													
		140%	130%	120%	110%	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
		14	13	12	11	10	9	8	7	6	5	4	3	2	1
0%	0,00	0,001788214	0,00192577	0,00208625	0,00227591	0,0025035	0,00278167	0,00312938	0,00357643	0,0041725	0,005007	0,00625875	0,008345	0,0125175	0,025035
2%	0,50	0,357642857	0,38515385	0,41725	0,45518182	0,5007	0,55633333	0,625875	0,71528571	0,8345	1,0014	1,25175	1,669	2,5035	5,007
4%	1,00	0,715285714	0,77030769	0,8345	0,91036364	1,0014	1,11266667	1,25175	1,43057143	1,669	2,0028	2,5035	3,338	5,007	10,014
6%	1,50	1,072928571	1,15546154	1,25175	1,36554545	1,5021	1,669	1,877625	2,14585714	2,5035	3,0042	3,75525	5,007	7,5105	15,021
8%	2,00	1,430571429	1,54061538	1,669	1,82072727	2,0028	2,22533333	2,5035	2,86114286	3,338	4,0056	5,007	[illegible]	10,014	20,028
10%	2,50	1,788214286	1,92576923	2,08625	2,27590909	2,5035	2,78166667	3,129375	3,57642857	4,1725	5,007	[illegible]	8,345	12,5175	25,035
12%	3,00	2,145857143	2,31092308	2,5035	2,73109091	3,0042	3,338	3,75525	4,29171429	5,007	6,0084	[illegible]	10,014	15,021	30,042
14%	3,50	2,5035	2,69607692	2,92075	3,18627273	3,5049	3,89433333	4,381125	5,007	5,8415	7,0098	[illegible]	11,683	17,5245	35,049
16%	4,01	2,861142857	3,08123077	3,338	3,64145455	4,0056	4,45066667	5,007	5,72228571	6,676	8,0112	10,014	13,352	20,028	40,056
18%	4,51	3,218785714	3,46638462	3,75525	4,09663636	4,5063	5,007	5,632875	6,43757143	7,5105	9,0126	11,26575	15,021	22,5315	45,063
20%	5,01	3,576428571	3,85153846	4,1725	4,55181818	5,007	5,56333333	6,25875	7,15285714	8,345	10,014	12,5175	16,69	25,035	50,07
22%	5,51	3,934071429	4,23669231	4,58975	5,007	5,5077	6,11966667	6,884625	7,86814286	9,1795	11,0154	13,76925	18,359	27,5385	55,077
24%	6,01	4,291714286	4,62184615	5,007	5,46218182	6,0084	6,676	7,5105	8,58342857	10,014	12,0168	15,021	20,028	30,042	60,084
26%	6,51	4,649357143	5,007	5,42425	5,91736364	6,5091	7,23233333	8,136375	9,29871429	10,8485	13,0182	16,27275	21,697	32,5455	65,091
28%	7,01	5,007	5,39215385	5,8415	6,37254545	7,0098	7,78866667	8,76225	10,014	11,683	14,0196	17,5245	23,366	35,049	70,098
30%	7,51	5,364642857	5,77730769	6,25875	6,82772727	7,5105	8,345	9,388125	10,7292857	12,5175	15,021	18,77625	25,035	37,5525	75,105
32%	8,01	5,722285714	6,16246154	6,676	7,28290909	8,0112	8,90133333	10,014	11,4445714	13,352	16,0224	20,028	26,704	40,056	80,112
34%	8,51	6,079928571	6,54761538	7,09325	7,73809091	8,5119	9,45766667	10,639875	12,1598571	14,1865	17,0238	21,27975	28,373	42,5595	85,119
36%	9,01	6,437571429	6,93276923	7,5105	8,19327273	9,0126	10,014	11,26575	12,8751429	15,021	18,0252	22,5315	30,042	45,063	90,126
38%	9,51	6,795214286	7,31792308	7,92775	8,64845455	9,5133	10,5703333	11,891625	13,5904286	15,8555	19,0266	23,78325	31,711	47,5665	95,133
40%	10,01	7,152857143	7,70307692	8,345	9,10363636	10,014	11,1266667	12,5175	14,3057143	16,69	20,028	25,035	33,38	50,07	100,14
42%	10,51	7,5105	8,08823077	8,76225	9,55881818	10,5147	11,683	13,143375	15,021	17,5245	21,0294	26,28675	35,049	52,5735	105,147
44%	11,02	7,868142857	8,47338462	9,1795	10,014	11,0154	12,2393333	13,76925	15,7362857	18,359	22,0308	27,5385	36,718	55,077	110,154
46%	11,52	8,225785714	8,85853846	9,59675	10,4691818	11,5161	12,7956667	14,395125	16,4515714	19,1935	23,0322	28,79025	38,387	57,5805	115,161
48%	12,02	8,583428571	9,24369231	10,014	10,9243636	12,0168	13,352	15,021	17,1668571	20,028	24,0336	30,042	40,056	60,084	120,168
50%	12,52	8,941071429	9,62884615	10,43125	11,3795455	12,5175	13,9083333	15,646875	17,8821429	20,8625	25,035	31,29375	41,725	62,5875	125,175

Green Design Pilo1

Figure 12: Heatmap new Repairability Indicator

2.6 Plans for the next phase

Considering the results from the data analysis of ESP as well as the try outs with samples in all relevant sustainability pillars (recycling, reuse and repair), there will be a new concept of ESP generated. In the next phase pilot 1 provides a new set of data to the collaborating partners in the project. The new innovative design elements will improve the ease of disassembly. Furthermore, a reduced material mix in the housing will enable the recycling of organics.

In the end of the project the sustainability dashboard that is filled by the input of the partners will demonstrate the improvements of an eco-design in a reduced LCA. The new indicator of repairability will additionally visualize the design decisions.

3 Pilot 2: Tyre Sensor

3.1 Initial state of the pilot.

The aim of the second use case is the eco-design of tire pressure monitoring sensors (TPMS). In the current situation, the tire pressure monitoring system follows a linear lifecycle, in which the full system is disposed of each time that a tire is exchanged or the battery of the system is empty. TPMS, like many other car electronics components, have been always designed focusing on their functionality and restrictive legislative requirements, link to linear use. So, sustainability and circularity aspects have never been considered as relevant. Also, their correct EoL management has never received much attention. As already mentioned for ESP units, also TPMS are negatively influenced by the absence of both a dedicated European/national regulation imposing their extraction from ELV wheels and a dedicated market for secondary components/materials. Hence, these TPMS are not disassembled from ELV wheels but are shredded together with the rest of the car components. This behaviour creates big economic losses for the entire automotive value chain both in terms of lost profits and lost volumes of secondary materials/spare parts that could have been re-introduced in the market. Again, all this has a high negative impact in terms of natural resources depletion and supply chain criticality (considering the current semiconductor crisis). So, there is an urgent need for adopting new eco-design logics to ease both the disassembly, repair, and recycling of TPMS, so to make their EoL management a profitable business.

3.2 Expected outcome

The vision of this pilot is a new version of the TPMS based on eco-design principles and sustainable materials. In terms of TPMS design, both novel sealing procedures and production logics will be assessed to ease both the disassembly of TPMS cases and desoldering of single electronic components from the main board. In addition, to increase the circularity performance of the tire sensor of the future it is envisioned that the traditional FR4 PCB needs to be replaced. To that end green PCB substrates will be compared with traditional FR4 PCBs assessed to design circular TPMS. Continental will be supported by a specific Digital Twin (DT). The DT will A) provide information on critical and valuable components to be disassembled, B) provide useful disassembly instructions, C) increase the awareness of carmakers/car parts suppliers about the recovery of critical materials from ELVs, D) increase the information/knowledge sharing between car parts suppliers/carmakers and different actors managing ELVs, E) quantify the improvement of minor/critical elements recovery through disassembly.

The main objectives of the tire sensor use case are:

- Improve compliance with market requirements (e.g., IPC A610 for PCBs, IMDS 14.1, ETRTO norms, EU ELV Directive 2000/53/EC Article 2).
- Extend product lifetime and fulfil governmental requirements to provide used parts to the market.
- Reduce the CO2 footprint & energy consumption of products.
- Ease access and removability of electronic parts.

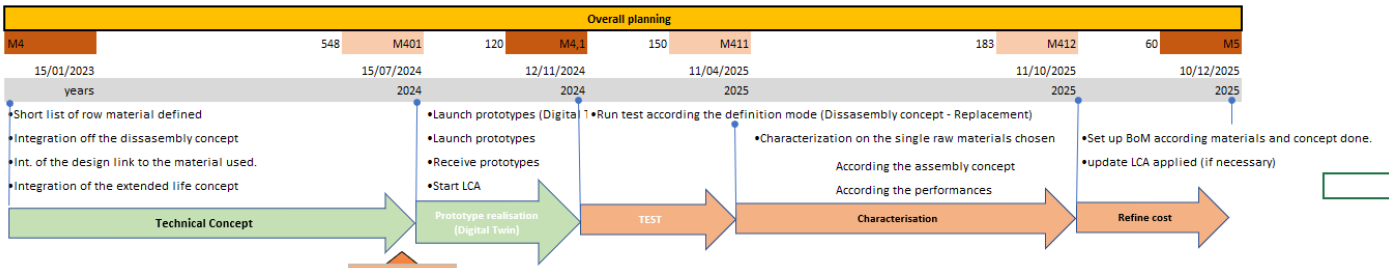
3.3 Defined targets

The following targets have been set for the TPMS use case (all the data are a comparison between the original layout of TPMS vs circular/sustainable layout of TPMS):

1. Reduce the LCA score by 20% overall (from current high runner to the new concept).
   - The current level of disassembly of the old product is 35 %, target is 60 % for the new product.
   - The dismantling level of the old product is 54 %, target is 100 % for the new product.
   - The recycling content level of the current product is 2.4 %, target is 69 % for the new product.
2. Use of design for recyclability to enable a correct sorting of components by family, using continental recycling passport as a KPI (for the moment).
3. Use of circular design to enable disassembly and repair of products, using continental recycling passport as a KPI (for the moment).

3.4 Performed activities and current state of targets

Main activities to be implemented within the TPMS use case:



3.4.1 Technical Concept definition

There are currently two concept definitions (named respectively BADGE and CAGE) we are developing with different technical bricks related to eco design concept:

- Exchangeable battery (under Patent process 2023E06020 FR).
  - BADGE: Top concept assembly leading to use less parts compared to cage concept, but with a higher precision in term of part manufacturing.
  - CAGE: Side concept assembly leading to use more parts compared to badge, but with a cost impact lead by the number of parts.
- Sustainable PCB with two different approaches and material suppliers.
  - AT&S approach: AT&S is providing a solution closer in terms of performance to the FR4 standard used in automotive. It has a less sustainable performance compared to the second

approach with JIVA product but provides circular economy perspectives and potential component recovery solutions (Figure 13).

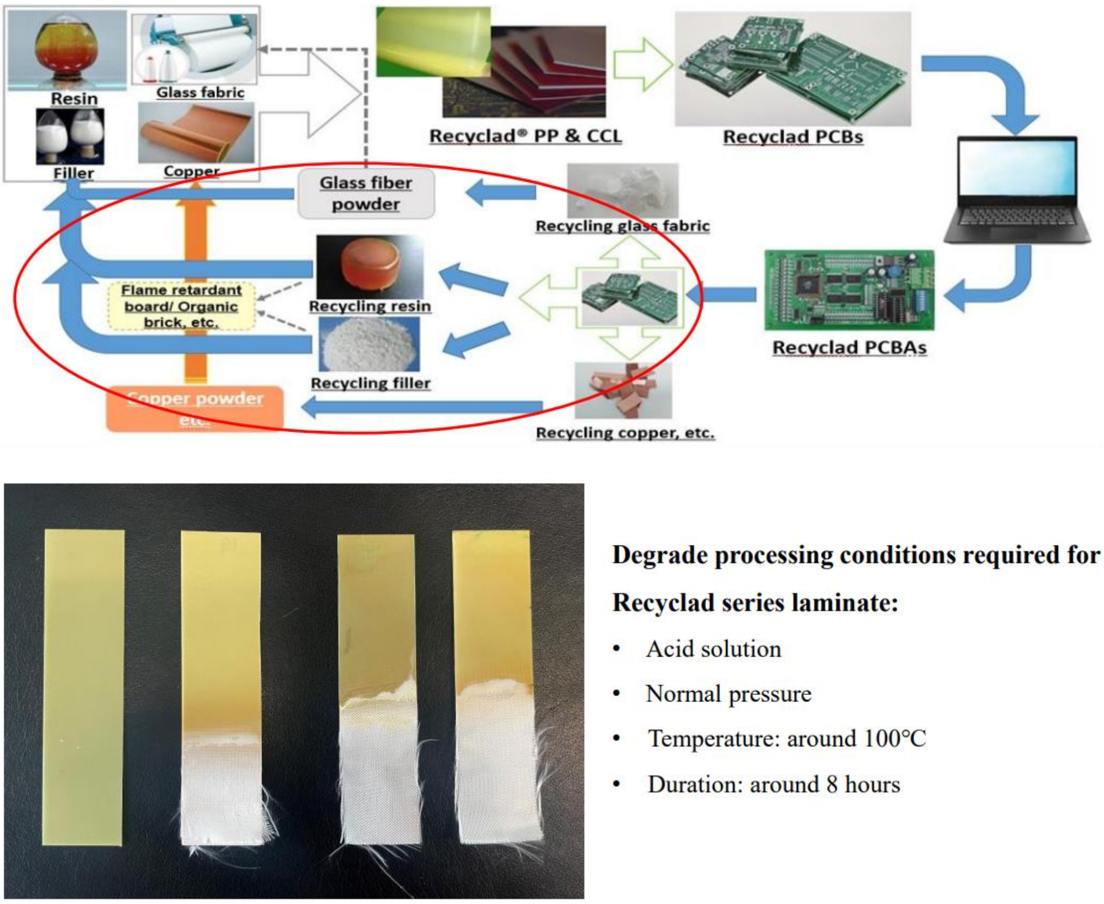


Figure 13: AT&S approach for more sustainable PCB.

- JIVA approach: SOLUBOARD ® solution, focusing on low carbon footprint solution (up to 95% smaller) from about 17kg of carbon footprint per square meter compared to 5.5kg to the Soluboard ® solution thanks for example to the use of natural fiber instead of glass fiber (see Figure 14). Furthermore, the solution from JIVA is recyclable. In additional this technology can be used with standard recycling processes with positive effect because the epoxy resin and brominated flame retardant are removed. Continental is developing technical solutions with JIVA and will check within the TPMS product the technical performance within an automotive application. In addition, Continental will investigate solutions about hardware component recovery with this technology.

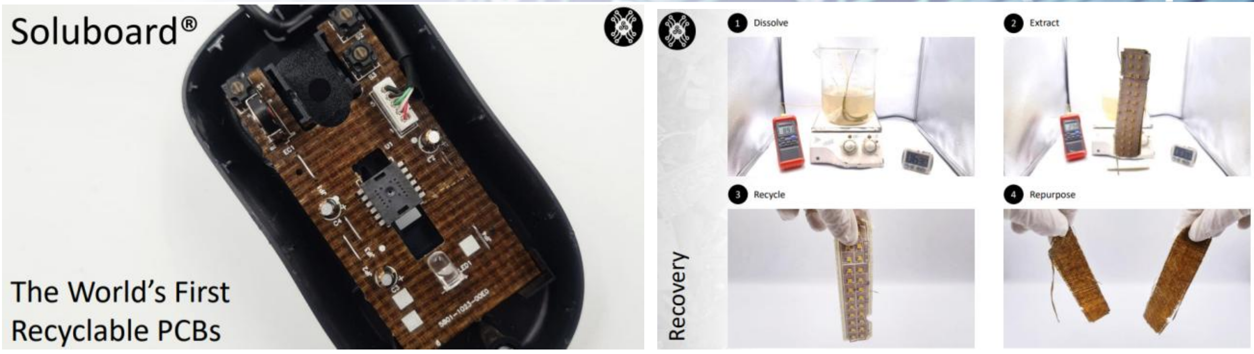


Figure 14: Jiva Materials Ltd | The World's First Fully Recyclable PCB Substrate) – Publication No. W02018/234801)

- Recyclable concept, link also to the circular economy.
    - For both concepts the goal is to be able to disassemble the different parts, able to remove and/or exchange them within the suitable environment for electronics maintenances.
- Sustainable plastic raw material.
    - Both concepts are developing the same plastic raw materials, with 3 philosophies to reduce the carbon equivalent footprint:
        - Eco friendly raw material (out of petroleum);
        - Raw material using low carbon footprint by using green energy;
        - Raw material using a high level of recyclable material within his composition.
    - A full validation of these raw materials is done with the support of CRF, helping us to characterize the performances of these raw materials within an automotive environment. The data will be available by January 2025. All these tests have been defined by Continental, shared, and agreed with CRF.
- Rubber valve recyclable.
    - Development of a chemical formula with CONTI Tech for the rubber valve.
- Hardware components recovery concept.
    - Trials and concept development regarding the component recovery base of AT&S and JIVA technologies.
    - Development with ALFA of a low temperature solder past to be used for the prototypes and the characterization test in 2025.

According to these concepts sustainable performances are evaluated using the digital tools developed within CIRC-UITS with a tool related to the concept evaluation within the development and a Digital Twin able to provide data related to the protocol of disassembly (see Figure 15).

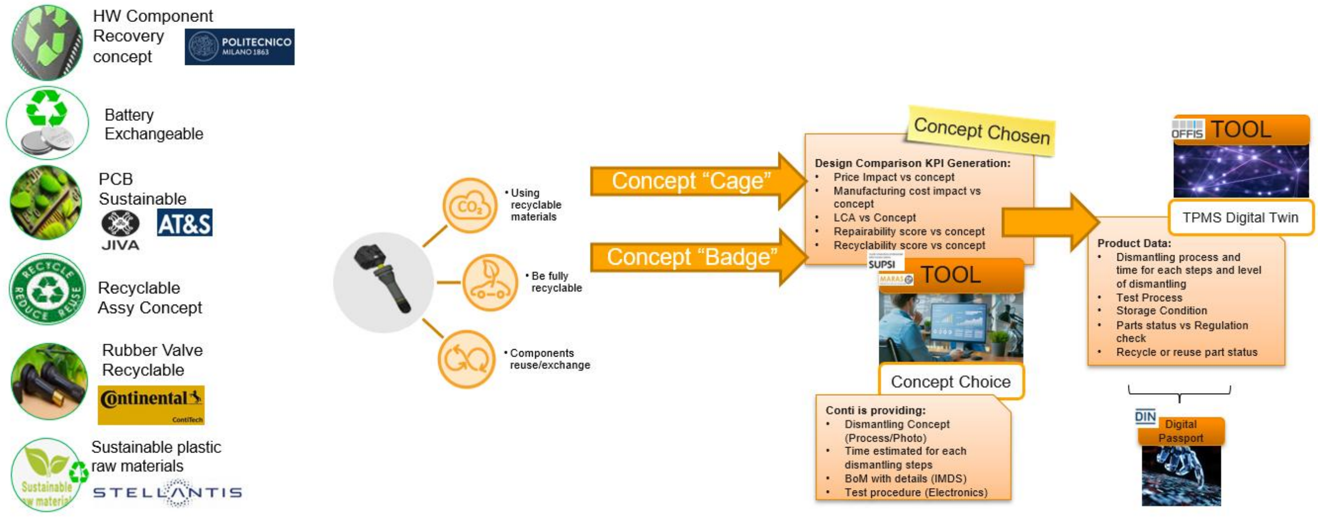


Figure 15. Technical concepts definition.

3.4.2 Prototype realization.

The concepts (3D Printed solutions) are currently under evaluation based on ergonomic performance improvement (how to disassemble). In parallel, evaluation of the different concepts based on the environmental KPI defined and currently are ongoing and will be further developed in 2025. Based on this approach a single concept; based on KPI performances and the best solutions in term of raw material, concept and maturity of technology will be set up.

3.4.3 LCA calculation and the digital twin tool leading to the recycling passport creation

Based on GWP 100 Kg CO2 eq. and the ISO 14040, the current product is providing about 0.75 GWP 100 Kg CO2 eq. within a Cradle to Grave life cycle and a bottom-up analysis. The detailed LCA calculation is currently confidential.

For the new concept, the LCA on carbon equivalent and repairability according the EN4554 together with the Digital twin are ongoing, to be realized in 2025.

3.4.4 Test and improvement.

The new concepts provide improvements on different elements. These elements will be measured in 2025 within the tools developed by the CIRC-UITS stakeholders and digital twin.

- LCA:
  - Using low LCA plastic.
  - Having the possibility to have recycled HW components (key factor to improve the LCA);
  - Having within his concept an eco-friendly mechanical design, able to replace components and put the product again on the market; improving also the LCA.
- LEVEL OF DISASSEMBLY: Within the repairability the level of disassembly will be evaluated for the current and new product using the tool developed by CIRC-UITS team. The KPI is going to be set up for the current and the next generation of sustainable product.

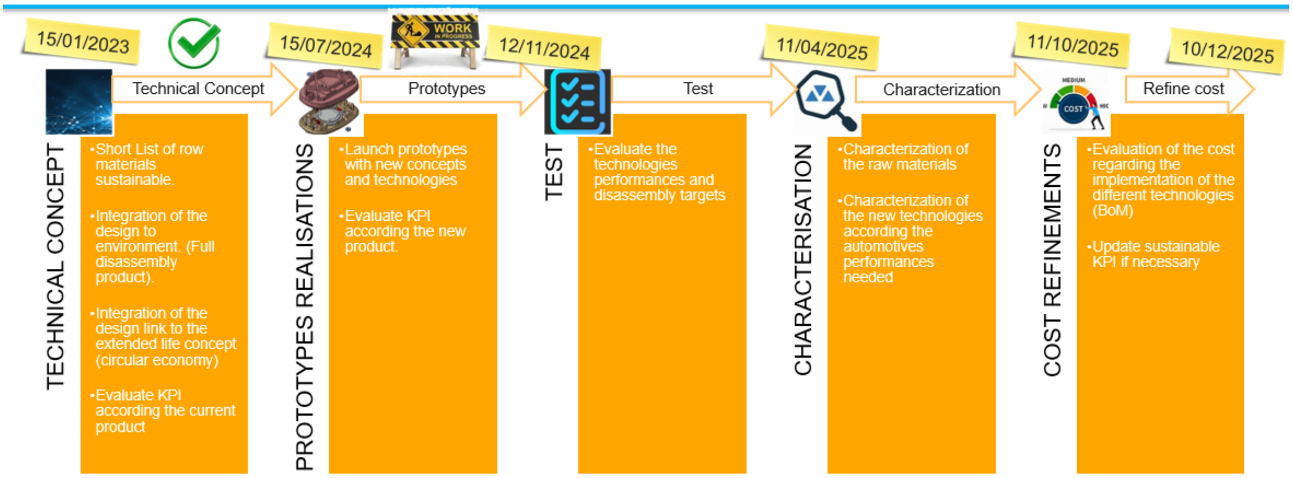
The characterization (performances tests) will be done in 2025 based on sample and simulation.

3.5 Innovative aspects compared to SOTA

- Eco friendly concept: The next generation of TPMS are now able to be fully disassembled including the Lithium-Ion battery (currently one of the main reasons of the end of life of the product). This increases the life cycle of the product and allows circular economy of the battery.
- Plastic element, with ecofriendly raw materials, then using assembly concept allowing the reuse and recyclability of the different parts. In additional the ecofriendly concept allows us to be ready for the circular economy by replacing or reusing all the components within the product.
- Main innovative aspect: more sustainable PCB, allowing us an improvement on LCA of the PCB and allowing us to recover copper and electronic component at the end of the life of the PCB.

3.6 Plans for the next phase

For 2025, test, characterization and refine cost base on the prototypes will be set up:



Detailed recycling assessment will be performed by the application of the Recycling Flowsheet Simulation Models as defined in WP3. The results will be used to provide physics and industrial recycling technology driven Design for Recycling feedback for the Tire Sensor, provide recycling KPIs to be integrated into Continental's recycling passport and demonstrate effect of disassembly on recycling performance and provide advisory.

4 Pilot 3: Green In-Mould Electronics

4.1 Initial state of the pilot

In-mould electronics (IME) is an example of structural electronics, where the electronics are integrated into an object with a 2½ or 3D-shape. It can provide functionalities to the object by integrating multiple electronic components (e.g. light source, sensors, actuators) on a surface/object. Through this integration the product showcases several advantages compared to traditional combinations of plastic components with electronics. Advantages are for example a space/weight reduction, omitting the need for a separate PCB, free-form design, and decreased production process complexity. Structural electronics is built up using various steps starting with printing materials on flat thermoplastic substrates (see Figure 16): 1) thermoplastic substrate, 2) printed graphics, 3) printed dielectric (non-conducting) materials, 4) printed electric circuitry using conductive inks, 5) components added by (printed) adhesive technology. The shape of the part is modified to its final 2½ or 3D shape using 6) high-pressure thermoforming. A final step of (not shown) injection moulding is often necessary to provide rigidity and encapsulation of the printed electronics.

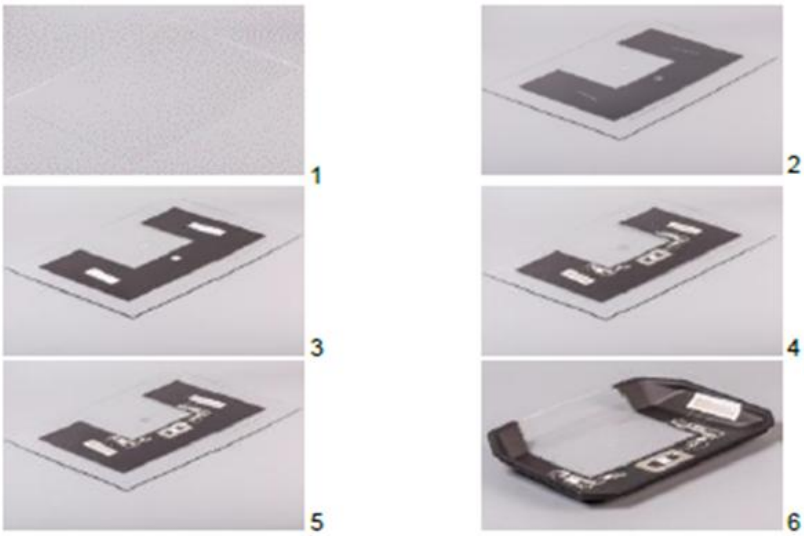


Figure 16: process to create 3D injection moulded printed electronics.

Parts manufactured through this technology have a reduced environmental footprint compared to traditional electronics production methods using for example mechanical buttons and PCBs. However, the range of electronic functionalities that can currently be integrated is limited to small and simple components. Additionally, the printing technology for structural electronics requires further research, such as advancements in materials and process conditions specifically designed for the thermoforming and injection moulding stages. These limitations hinder adoption of this next generation of electronics in challenging sectors like the automotive industry.

Furthermore, another big issue presents itself with structural electronics. While this technology yields aesthetically pleasing parts with lower CO2 footprint, this way of working does not facilitate dismantling of electronics that enables repair or recycling of valuable components and materials due to the fusion between plastics and electronics. Consequently, if an IME part fails or malfunctions, it usually must be replaced rather than repaired.

4.2 Expected outcome

To enthuse industry of the benefits of in-mould electronics compared to state of the art a demonstrator for the automotive industry will be developed. For this it is required to introduce more complex electronic functionality into the in-mould parts. Therefore, the approach and processing techniques to create printed electronics specific for thermoforming and for IME will be re-evaluated and improved where possible. The focus lies on adapting the design of print to facilitate much higher quality of IME.

Furthermore, in our vision a crucial component of the story to advance IME to the next phase is opening the possibility for repair and or recycling. If the complexity and costs of these parts are increasing it is simply not acceptable that there is no way of repairing or recycling. The EU is also recognizing this fact and is placing pressure on car manufacturers to utilize new technology and technology with the potential for repair. In terms of IME's design, novel production technologies will be tested to ease both repairability of faults and the desoldering and replacement of single electronic components from the substrate. In summary, the main objectives for this pilot to advance;

- Demonstrate integration of more high-end PCB-like functionalities into sustainable IME for automotive industry;
- Improve design of printed electronics to reduce production issues and increase initial yield of complicated printed and thermoformed designs;
- Demonstrate repairability for thermoformed printed electronics and IME;
- Develop (semi-automated) repair procedures for issues during production phase of printed and thermoformed electronics;
- Reduce the environmental impact of IME products;
- Assess new types of low-temperature solders for easier disassembly and improved sustainability.

The IME use case will be focusing on both BoL and EoL to increase the circularity performance of IME parts. A LCA of the pilot device should demonstrate the potential advantageous result on environmental footprint of utilizing the printed electronics technology with in-mould processes. Furthermore, if repair of IME devices is technologically feasible LCA will be performed to demonstrate potential advantageous results of repair of a broken device compared to recycle and creation of a new device.

4.3 Defined targets

A significant portion of the pilot is relatively low TRL technological development, which complicates assigning specific target values. The following targets have been set for the IME use case:

1. Integrate PCB functionalities into sustainable IME (60% to 80% smaller footprint than Arduino Uno);
2. Upscale printing of the increased complexity demonstrator from lab-scale to industrial scale facility.
3. Implement disassembly technology for the potential repair/recycle of thermoformed and IME devices;
4. Demonstrate IME repairability through lab tests;
5. Develop fault detection and repair procedures during production phase;
6. Reduce the environmental impact of a broken IME product by 50% by utilizing repair, instead of SOTA options of recycle and remake.
7. Improve printing technology process conditions to be compatible with ultra-low temperature solders, which is currently not possible. Implement these solders in new demonstrator device to increase TRL level, allow easier repair and reduce environmental impact of IME device.

4.4 Performed activities and current state of targets

Pilot 3 aims to create a green IME part for the automotive industry to pave the way for replacing the traditional combination of electronics and plastic parts used in cars. Together with all main technology partners from the pilot (TNO, TRACXON, ALPHA, CRF, POLIMI), plans and goals were discussed, refined and agreed upon. For the low TRL technical innovative work on repair concepts for IME devices it was decided to utilize an existing mould and device design from TNO. This design is also used in other EU projects (TREASURE: grant agreement No° 101003587) for research into disassembly and recycling. This device is simple with respect to functionality and is well known from previous work. It is therefore the ideal vehicle for innovative low TRL studies into first ever repairability of IME, LCA comparisons of recycle versus repair and investigation of automated detection and repair technologies.

For the other parts of the planned work, it was decided to a newly designed thermoformable printed electronics demonstrator with properties, functionalities and design features of interest for automotive industry. This new demonstrator device brings together the best the pilot partners have to offer. CRF provided input on wishes from automotive industry with respect to design, aesthetics and functionalities. The requirements are translated to a printed electronics design by TNO, who are experts in this field, with the eco-design requirements in mind. Then, TNO's electrical design and 3D mould was reviewed by the ALPHA team, who have ample experience in optimizing circuits specifically for 3D applications. ALPHA is furthermore able to supply several innovative materials specifically developed for thermoforming; such as two-step UV curable thermoformable substrates and low TRL ultra-low-temperature solders (which have to be benchmarked first). TRACXON, at the end of the line, will print the design at their industrial facility and is an important discussion partner for all steps of the process.

In summary, below are the main topics under investigation within the IME use case, with the corresponding targets those activities contribute too.

- Design new thermoformed test vehicles (Target goals 1,2)
    - First version: intermediate complexity
    - Second version: full functionality
- Benchmark ultra-low-temperature solders from Alpha Materials and investigate potential implementation into thermoformed test vehicles. (Target goals 7)**.**
- Low TRL technology: Manufacture, disassembly and repair of deliberately defective devices and (Target goals 3, 4, 5)**.**
- LCA of repair compared to recycle (Target goal 6).
- Automatically detection and repair of defects (Target goal 5)**.**

4.4.1 Design of new Automotive Thermoformed Demonstrator

Considering that starting from nothing and reach a full automotive interior part was not likely to be successful immediately, it was decided to do the design of the demonstrator in two phases and increase the difficulty where possible after the first version. Together with all pilot partners, a wish list was defined for the two generations of demonstrator. The Table 2 below lists those requirements and specifications. CRF had a big say in the design and components to be included, as they are a potential interested end-user of such a 'Plastronics' (i.e. IME) product in their products. The demonstrator was designed according to specifications from TACTOTEK® (of which TRACXON has the license) which ensures the possibility to upscale the part and implement in the automotive industry. The specifications include e.g., line width, stretch design, capacitive touch and sliders design as well as automotive certified LEDs.

Table 2: Specifications of two versions of automotive demonstrator for pilot 3.

	Test vehicle V1	End-goal: full automotive demonstrator
Substrate	Standard PC (polycarbonate).	Alpha materials polycarbonate, 500 micron gloss finish or 250-micron matt finish.
Encapsulation	Just thermoforming, no additional encapsulation	Thermoforming with an extra encapsulation layer (but not IJM)
Circuitry	Test circuitry (silver/copper).	Fully functional circuitry. Alpha silver inks for thermoforming.
PCB	External PCB to drive (Arduino)	No external PCB. Only externally powered.
SMD components	LEDS. Capacitive touch sensor/sliders.	Additionally: 3D gesture recognition antenna with all required electronic components, flexible OLED screen
Bonding	Isotropic conductive adhesives (standard in printed electronics)	Ultra Low-T solders from ALPHA (potentially for a part of the components)
Shape	Flat or basic curve.	More elaborate 3D if design available and feasible.
Defects	Intentional defect in circuitry lines, intentional removal or misalignment of LEDs	Real production defects or randomly applied post-printing/bonding
Disassembly	No cover yet so no disassembly	Design with temporary bonding layer. Manual disassembly. Research required for bonding layer with thermoform cover.
Method of repair	Manual repair by trained technician.	**Include computer vision for** defect detection at POLIMI. Ideally component replacement with COBOT at POLIMI.
Testing and requirements	Lab testing functionality and circuitry.	Automotive interior part requirements tests. Thermal cycling, humidity, thermal shock, Hot Storage, Shear Test at CRF. Not sure if it works without IJM cover.
Timeline	Year 1-2	Year 2-3

Production	Lab of TNO and TRACXON	Production at TRACXON
LCA	None	Full product LCA

4.4.1.1 Demonstrator V1

The V1 demonstrator was made with a thermoform mould from TNO that has a large flat part and curves off on the sides. This gives room in the middle for incorporation of electronic components on the flat part, and it has the looks of a typical car dashboard component. Substrate was chosen to be PC, as is most used in car parts and in in-mould electronics production. Functionalities to be included are several LED and capacitive touch sliders and buttons. Testing was to be done at TNO facilities and design reviewed by TRACXON. See Figure 17 for the design. Production of V1 demonstrators at TNO and TRACXON has been performed successfully, creating ten functional parts in a process design that is in line with unscalable production processes. The process yield was determined and was over 90%. The mechanical and electrical performance of the inks, location of the sensors, placement and functionality of the LEDs, etc. were all reviewed. Several design improvements came to light for the next version with respect to the general design, graphic layers, lightguides, button design, slider design and pick and place processes.

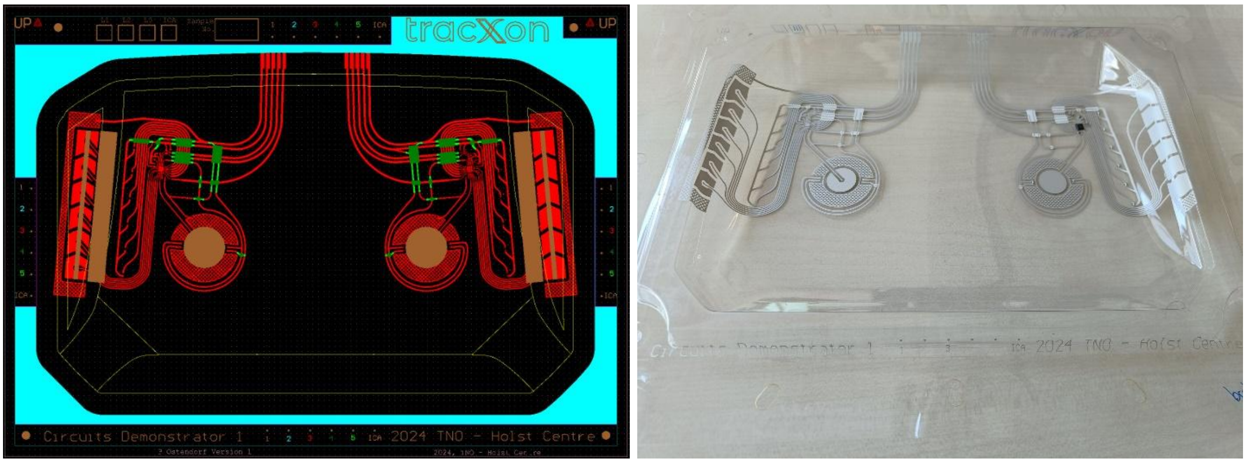


Figure 17. Left: Design of intermediate demonstrator. Right: printed and thermoformed real device, not all components were placed.

4.4.1.2 Final Demonstrator

After testing and review by TNO and TRACXON, TNO developed the second version, now with significantly increased number and complexity of functionalities. Consequently, the number and size of components increased, which complicated the circuitry design while still requiring adherence to the same design rules. Due to this complexity, the team decided to complete and test the full design as a rigid PCB before committing to the printing process. This approach allowed all functionalities to be thoroughly tested. Towards the end of 2024, the complete design was finalized. Compared to version one, it includes several key modifications:

- Additional LEDs to improve visibility of buttons and sliders;
- Side firing LEDs instead of top firing;
- Shifting sideways of the capacitive touch sliders;
- Addition of 3D gesture recognition antenna in the middle;
- Addition of a flexible OLED screen on the top;
- All electronic components to run the device integrated (chips etc.) on the flat parts of the foil;

- The total design consists of seven different printed layers.

At TRACXON's facilities, the initial production process achieved a yield of over 90%. However, this final version is considerably more complex so maintaining such high yields in later stages will be more challenging. The primary step in reducing environmental impact is to optimize both design and process conditions to achieve the highest possible yield. An optimized design minimizes failures during production and extends product lifespan, making it preferable to repair or recycling options.

The design underwent several rounds of review with TNO's print and electrical design experts, followed by assessments from TRACXON's print experts. Finally, ALPHA team completed a comprehensive review, covering the 3D thermoform mould, electrical design, and component selection.[1] This thorough review process is key to ensuring high production yield. The report was shared with the pilot partners and discussed with TNO experts, leading to a few more design modifications. As of late October 2024, a design freeze is in place (see Figure 18), and screens for printing have been ordered. Initial test prints are scheduled for December 2024. TRACXON will then take over and research up-scalability of the process at their site.

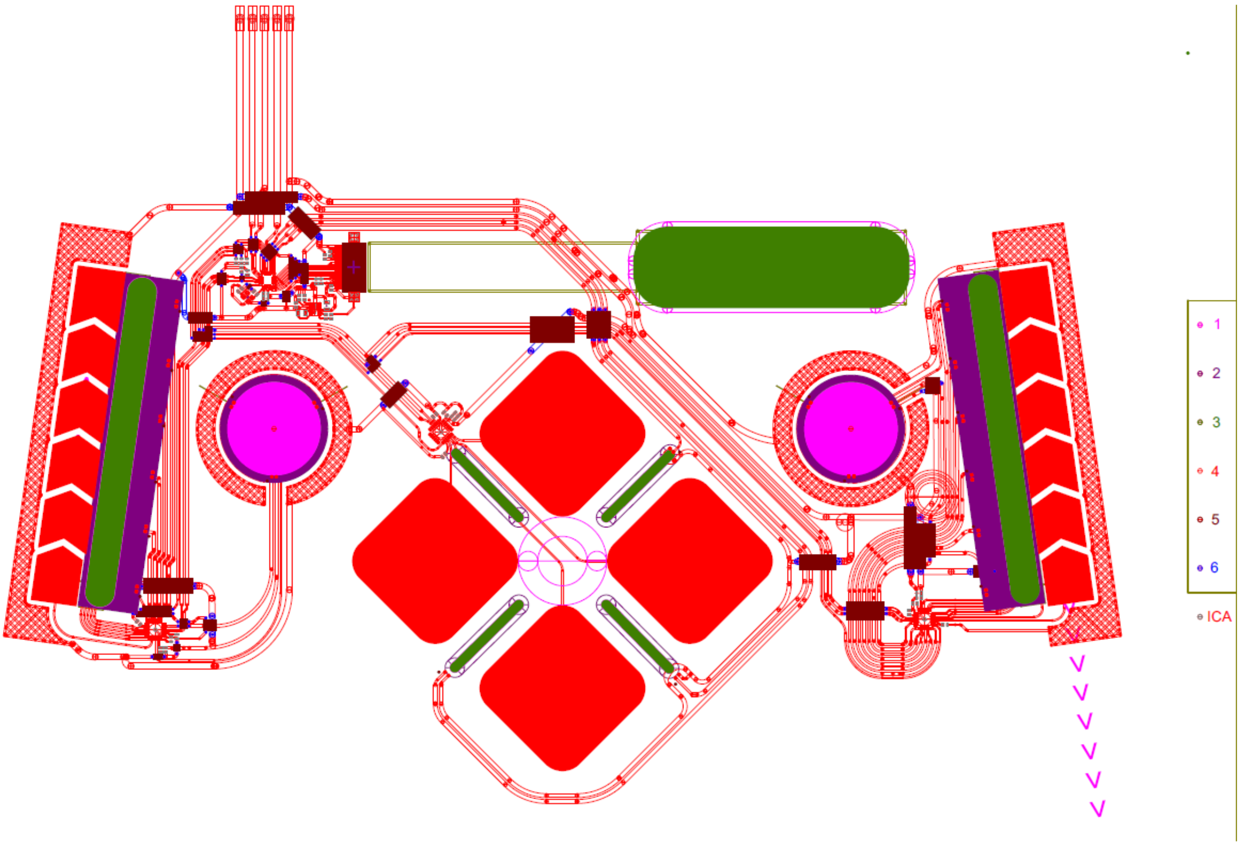
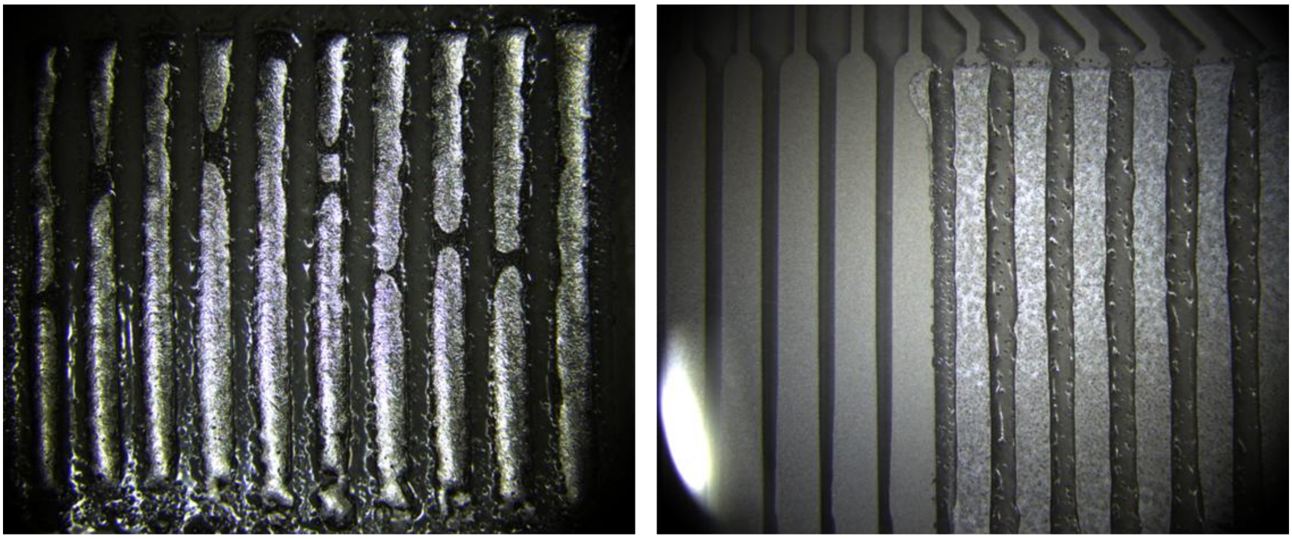


Figure 18: full demonstrator device design. Layer 1: opaque white, layer 2: translucent white, layer 3: graphic black ink (not filled in here), layer 4: first silver circuitry layer, layer 5: di-electric isolation layer, layer 6: second layer silver circuitry, layer 7: isotropic conductive adhesive/solder.

[1] See ANNEX A – Alpha design review report of TNO pilot 3 demonstrator

4.4.2 Benchmark ultra-low-temperature solder

ALPHA developed low to ultra-low temperature solder materials. These would be an improvement on several important aspects (cost, environmental impact, functionality) over the currently used isotropic conductive adhesives in printed electronics but are typically not yet compatible with printed electronics processes. The International Standards do not cover this technology today, but IPC is currently working on the first release of an IME standard. ALPHA sent these materials at the beginning of 2024 to TNO. First, several wetting experiments were performed by TNO at that time. In this round of experiments the process conditions were checked, aligned and the equipment tuned in to work with these materials. In Figure 19 the first results of the test are shown. Good wetting of the solder on one of the baseline silver inks was seen, but also leeching of the solder into the silver, which is a typical problem when combining solder pastes with silver ink.



Sample with silver ink from top — *Sample with silver ink from the back*

Figure 19: first wetting tests performed with Alpha ultra-low-solder materials at TNO printing facilities.

After further discussions among ALPHA, TNO and TRACXON, a test plan was defined for the coming period.

- Circuitry and components: standard test pattern with three sizes of components (0402, 0603, 0805). Patterns are also suited for contact resistance measurements.
- Initial benchmark experiments to determine correct solder settings with TNO equipment and materials: completeness of soldering, wetting behavior, mechanical/chemical interactions, with/without N2.
- Select materials and substrates to benchmark on/with: PET, PC.
- Reference: FlexPCB, baseline printed silver, baseline printed copper
- Analysis: microscope (top/bottom), electrical, shear strength, flux behavior, etc.

Unfortunately, there have been some postponements with this work due to delays and setbacks in manufacturing and subsequent delivery of the ultra-low-temp solder materials. Furthermore, after initial testing at TNO it was found that the print design to benchmark solders has some flaws. As mentioned, a typical issue with soldering on silver tracks is silver leaching. Silver leaching, or silver dissolution, into solder can cause significant problems in electronics and solder joints. This occurs when silver from a component or a board coating dissolves into the molten solder during soldering, potentially weakening the joint and leading to reliability issues. To combat this issue, we can for example print more silver layers or protection layers.

However, the stacking of these layers under the solder pad has been suboptimal, resulting in cracks near the connection with the silver tracks. This has made results non-reliable and not a fair benchmarking process for the ultra-low-temp solders. This issue is currently being worked on.

4.4.3 Technology development: repair and refurbish of IME devices

One of the main innovative pillars for CIRC-UITS is enabling repair of electronic components, which you see recurring in several of the pilots. In mould electronics is a relatively new technology and the market has yet to fully embrace the new products made with it. This gives a rather interesting situation; on one hand it is difficult to perform low TRL research on potential repair of (production phase) faulty devices, since there are no production lines and there is ample experience or data on the subject. On the other hand, it can also be seen as an opportunity to develop this type of additional technology for recycling and/or repair; even before the initial technology is widely spread, which could make it easier to implement it.

This research topic was performed using an existing plastic mould design of TNO. It is called Flexlines design and has 132 LEDs integrated. The initial work here benefited from the research done in TREASURE, in which temporary bonding layers were integrated into the plastic device allowing the disassembly and removal of the injection moulded polycarbonate cover. While in TREASURE the goal of this disassembly was the further recycling of all individual components, in the CIRC-UITS case we could use several of these disassembled devices for repair purposes. We received several foils with integrated temporary bonding layer and then disassembled them from their polycarbonate covers to retrieve partially damaged printed foils. These foils from disassembled devices were electrically characterized and damage was manually detected and categorized. The types of damage that can occur are various and in various intensities; e.g., missing LEDs, broken LEDs, circuitry damage, damage in the conductive adhesive etc. An experienced technician repaired the damages. Figure 20 shows a set of typical damages and their repairs.

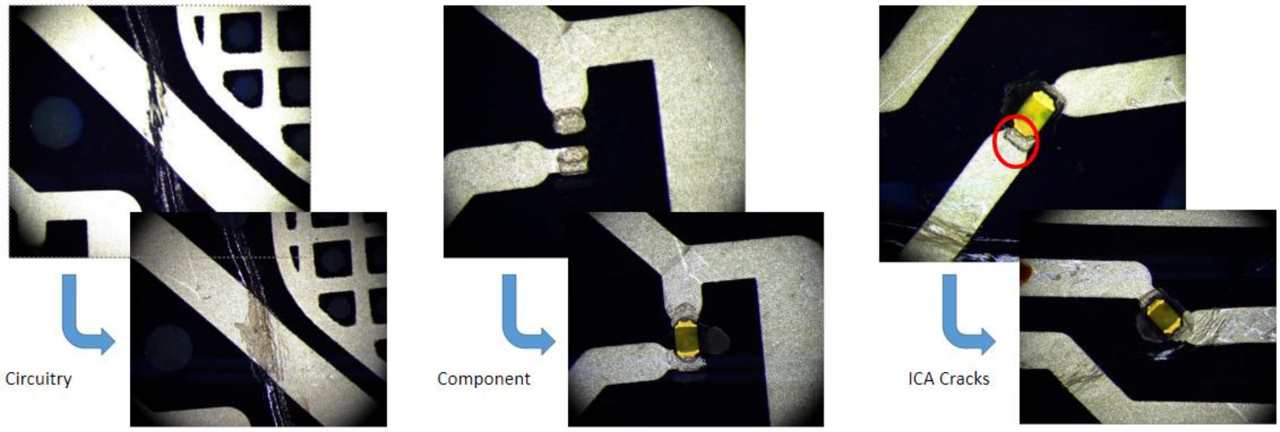


Figure 20 Set of various types of damages of disassembled IME devices and after manual repair.

These repaired foils were then re-processed for injection moulding and a new polycarbonate cover was injected over it. Depending on the level of repair that was performed on the foils, we found that re-manufacturing into a refurbished device with full functionality is possible after a second round of injection moulding (see Figure 21).To our knowledge this is the first time re-moulding of an IME product has ever been done. This means that in case of a damaged product that is not too severe (e.g., with an issue during production of parts) the device can be disassembled, repaired and refurbished with another plastic layer. This could potentially be a huge benefit compared to having to fully recycle/discard a product that failed freshly from the production line.

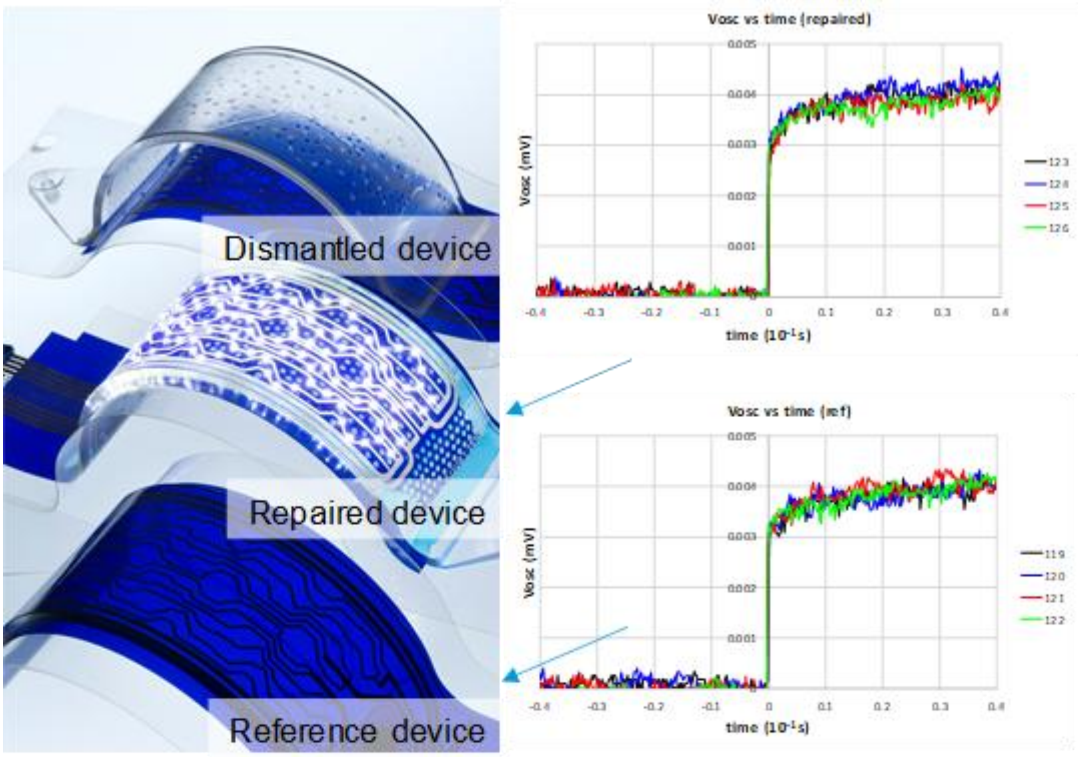


Figure 21: Electrical comparison between refurbished and reference device.

4.4.4 LCA Repair vs Incinerate

In the project several new ideas and frameworks for repair and repairability of electronic components and devices are introduced. In some pilots we are just looking at the question to what level repair is technologically feasible, while in other pilots we are also looking at the effect of repair on the LCA of a device to see if it makes sense economically or environmentally to perform a repair. Together with the experts from WP3 (MARAS has set up an approach for repair assessment and supporting KPIs, this is described in more detail in D3.1), some KPIs were defined to serve as a measure for the effect of repair. Some of these can be determined experimentally, and some can be derived by empirical estimations and own assessments and standards, due to lack of reliable data. Some, but not all, of these KPIs are:

- Disassembly time/cost;
- Energy consumption of disassembly and repair;
- Creation of waste or residue from disassembly and repair;
- Additional materials input needed and/or machinery;
- Saved primary resources;
- Reliability of repaired product;
- Expected life-time extension as a result of repair;
- Potential recyclability and recycling rates for materials and energy from discarded devices.

The quantitative KPIs with respect to recycling rates for material and energy recovery, waste and losses and (saved) resources as defined in this repair assessment approach are directly linked to the LCS&CA assessment methods as defined in WP3 for Recycling Assessment (MARAS) and will be applied for this (and other) pilots.

Some of these parameters were experimentally retrieved from a fixed set of device reparations performed. All the actions were documented; materials were weighed, process steps timed, waste collected, etc. We could then perform an LCA on the repair activities and compare this with LCA for the production of a new device and incineration for energy harvest of the broken device. With this initial screening, everything points in the direction that repair of an IME product in the production phase is environmentally beneficial compared to incineration and production of a new device. The detail of this result is influenced currently by a lot on non-fixed factors such as the number of repairs needed per device, the batch size of devices to be repaired (electricity for a curing step can be divided over more devices/repairs), electricity mix used, etc. Furthermore, from the initial technology experiments we did measure a 2 ± 2 % higher energy use for repaired devices compared to reference products. Higher energy use for a full lifetime can quickly add up in a negative way for the overall environmental impact. In our LCAs we therefore used several scenarios of increased energy use. Still, even in the worst-case scenario the impact of repair is lower compared to incineration of faulty and production of a new device. In Figure 22 we demonstrate the benefits (negative impact is beneficial) for a 4-device batch repair with 20 LED damage per device and 8 circuitry damages, with 3 different rates of potential device power use increase after repair. The only negative component can be found in ionizing radiation, due to the increased electricity of the device use during lifetime in case of a 4% worse energy use.

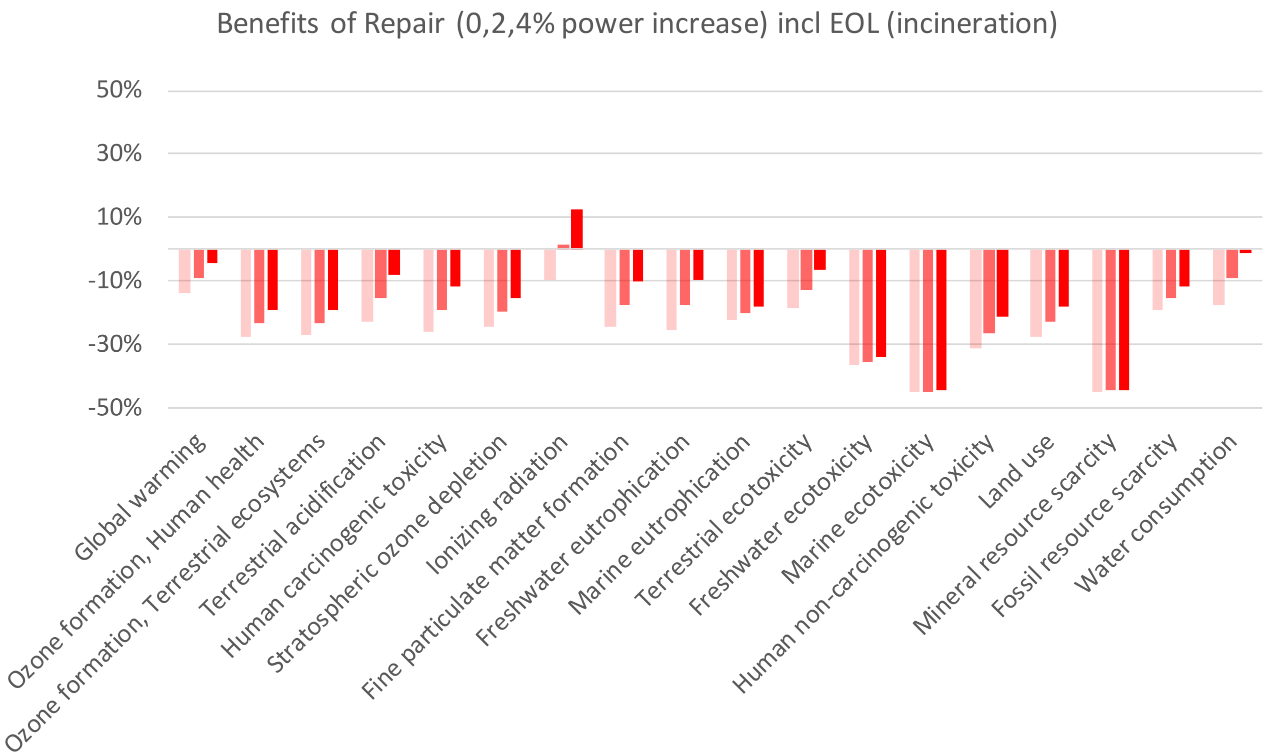


Figure 22 Repair versus incineration; repair of a batch with 4 devices.

In conclusion the current results indicate a lower environmental impact of repair than for incineration for energy recovery, even in suboptimal (and manual) repair scenarios. However, these are preliminary results and not yet optimized/finalized and should be interpreted with this in mind.

4.4.5 Automating repair work

In our current settings all detection of damage and all repair work was performed manually by a trained technician. This means several things; 1) dispension of materials such as silver ink is not fully optimized, 2) potential harm for manual workers, 3) potential for mistakes or faults, 4) time-consuming process. Especially the time component could have a negative effect on economic viability of repair, which is not part of the LCA comparison of repair. We identified two time-consuming steps in the repair process. The first one is the manual detection of the damage with a microscope, and the second is the manual placement of new LEDs (components). Compared to dispension of silver or conductive adhesive with a semi-automated dispension system and a microscope, which is rather quick and simple, the manual placement of new LEDs with a microscope and a set of tweezers is more finnicky and prone to error due to the small size of the components to be placed.

Potentially, the time for repair could be reduced drastically by both the automated identification of damage and the automated placement of LEDs. In our initial experiments, part of the LEDs was replaced using the pick and place machine (Figure 23 left); the same machine that places the components during production of a new device. A major issue presented itself here; the coordinates of all the LED positions had shifted compared to original (Figure 23 right). This has occurred due to the device undergoing several processing steps that have occurred since original component placement (thermoforming, injection moulding, curing steps, disassembly. Etc.), thereby slightly changing its dimensions and shape due to expansion and contraction. This meant that for each individual LED to be re-placed the coordinates need to be adjusted; increasing the time spent replacing the components by about ten-fold. Currently, therefore, manual placement is still the faster option. In CIRC-UITS, we are collaborating with partner POLIMI to automate this process. More details of this work will be presented in chapter 6.

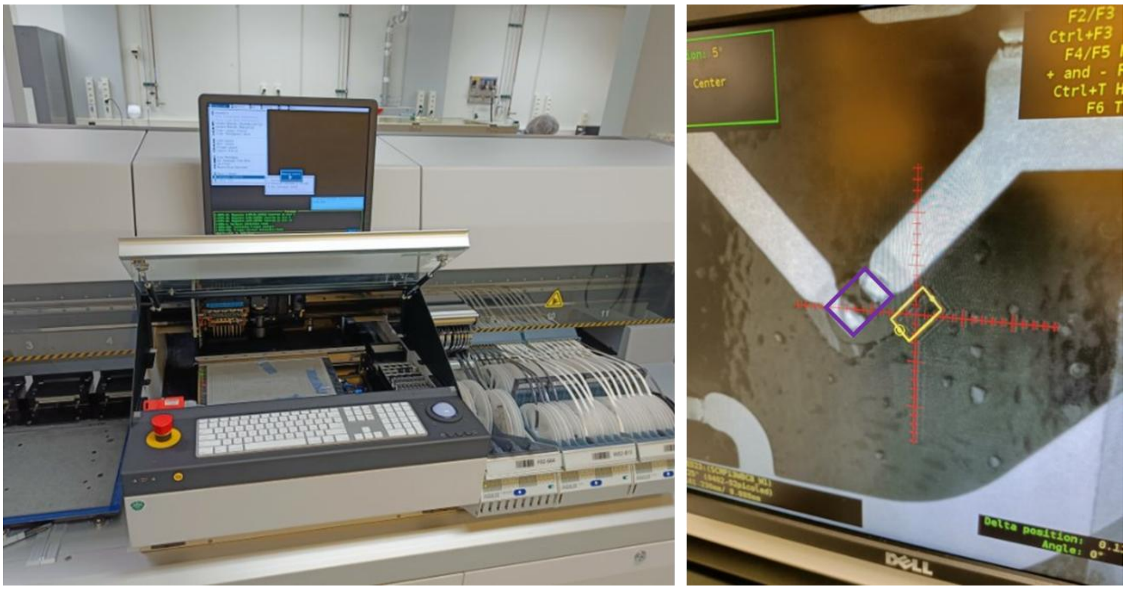


Figure 23. Left: Pick and place machine. Right: shifted coordinates of LED. Yellow box is original, purple box is new location.

4.5 Innovative aspects compared to SOTA

- Introduction of more complex and higher functionalities such as 3D gesture recognition antenna and flexible OLED screen into thermoformed devices. These functionalities are currently being included in the next version of the thermoform design.
- Integrating all required electrical components into the thermoformed device, omitting the need for an external PCB.
- First ever 'Refurbished' IME product. This is still a low TRL research topic, but the first demonstration of a fully functional disassembled, repaired and re-injection moulded IME device is a technological breakthrough.
- Use of low temperature solders in printed electronics and thermoformed products. Besides the obvious benefits, the added goal specifically for CIRC-UITS is to facilitate the IME repair process.
- Automated damage (missing components) detection and automated adjustment of coordinates for remanufacturing/repair work.

4.6 Plans for the final phase

4.6.1 Automotive demonstrator

In the remaining of 2024 the first prints will be done on the new design. Several materials from Alpha will be utilized for this. Some of the processing steps will likely have to be optimized, such as the printing, thermoforming, UV curing of PC substrate, lightguides, OLED screen integration etc. In 2025 the device will be evaluated and send to CRF for testing. We will furthermore experiment with thermoforming an additional PC layer on the component side of the device for mechanical stability and protection of the components, since we are not injection moulding with this design.

Once the process conditions have been verified at lab scale at TNO, TRACXON will translate these process conditions to their facilities for the upscaled production at their industrial site. (Production) data from this device will then also be gathered and shared with WP3 partners to perform an LCA and LCC analysis of this fully printed electronics automotive demonstrator.

4.6.2 Ultra-low temperature solders

Currently new screens are being designed to optimize the solder on printed silver benchmarking. We will then restart the benchmarking of these solders with our inks and processes. Afterwards the goal is unchanged, to investigate the ease of replacing components on thermoformed devices. This should allow potentially easier repair. Secondly, the goal is to utilize this material into the thermoformed automotive demonstrator. It would be an improvement on the environmental impact compared to conductive adhesive and, again, potentially eases removing and replacing components for repair purposes.

4.6.3 Technology development: repair and refurbish

TNO is finalizing an initial scientific publication on this topic, highlighting the success of the world's first repaired and refurbished IME devices in the CIRC-UITS project. Further research on these Flexlines devices will be mainly on automation steps together with POLIMI (see also chapter 6) and will thus likely merge with those activities.

4.6.4 LCA repair vs incinerate vs recycle

The initial LCA of the IME seemed to be in favor of repair actions. However, in this case we used incineration for energy harvest as the alternative option for the device to be discarded. Potentially, recycling this broken device to a certain extent will be possible in the future. If an IME device is disassembled the polycarbonate has been separated and the silver ink layer is also better retrievable. However, similar to repair, the technology is not mature yet to have reliable LCA models for it. This is unfortunate, since even sub-optimal recycling of a broken device could alter the balance in the LCA significantly compared to incineration. If silver and polycarbonate could be retrieved instead of incineration it might be more beneficial to perform a clean recycling of the broken product. Therefore, we continue to work on this topic with our partners and try to get potential LCA estimates, models and quantified recovery KPIs for recycling of disassembled IME devices, in order to improve the comparisons and find the best option from an environmental standpoint.

4.6.5 Automating repair work

We are putting effort in this part, as we have recognized that it could be an important pillar of the potential viability of repair work in IME devices. In chapter 6 more is explained on this topic.

5 Pilot 4: Obsolete PCB sorting

5.1 Initial state of the pilot

The fourth use case refers to obsolete printed circuit boards' sorting processes. End of Life PCB sorting in WEEE treatment plants currently involves the separation and classification of circuit boards for recycling, based on their characteristics, material and components.

The PCB sorting occurs in several steps.

1. Extraction from the device or appliance; some devices containing PCBs are manually or mechanically opened to extract and collect the circuit board. This stage is different based on the type of device. Small IT like laptops containing PCBs that present a higher commercial value are manually dismantled to maximize the printed circuits and electronic components recovery, as well as avoid damage in the instance of a possible interest for reuse. In the case of household appliances or devices containing lower grade PCBs, they are opened mechanically, and the electronic components are manually removed together with pollutants, batteries etc.
2. Disassembly step; some components present on the circuits board such as processors, memory, connectors, heat sinks etc. are removed and separated into different fractions. For example, aluminum heat sinks are sent together with the rest of aluminum scraps coming from different devices in a specific treatment plant, as well as copper connectors sent to copper recycling and so on.
3. Removal of hazardous materials; during the disassembly, hazardous or harmful materials present on the circuit board are removed. These materials are then destined for proper and safe treatment and disposal.
4. Classification; PCBs are classified based on their characteristics and composition. The main goal of circuit board classification is to obtain clusters of PCBs as homogenous as possible in order to send them to smelters to recover and recycle materials as efficiently as possible. At this point, the separation is mainly based on the presence of certain amount of gold (g/ton) and the possible references about the typology of product from which the PCB was extracted can only be detected by product experts.
5. Recycling: circuits boards are sent to recyclers (i.e., smelters) that, through a combination of pyro- or hydrometallurgical processes, extract the metals from the PCBs. This composition of the PCBs in terms of precious metals contained is linked to the sorting categories. The smelter will pay the plant according to the sorting efficiency (homogeneity of the sorting done) and degree of value of the material. The presence of penalty and disturbing elements as defined by the smelters will lower the value of the fractions. The number of subdivisions depends on plants internal procedures and input materials.

The PCB sorting process is currently done manually by highly skilled operators. So, the sorting performance strongly depends on the operator that is implementing it; this is time-consuming, not accurate and tiring work, that cannot ensure the same accuracy from the beginning to the end of the process. Nowadays the classification of PCBs is based on precious metal presence such as gold, silver, copper and palladium. To establish and boost the recovery processes of CRMs, improving sorting performance is the first step, indeed essential to increase the reliability of treatment plant outputs intended for smelters and other supply chain stakeholders.

The second issue that pilot 4 is targeting is the non-existent possibility for OEMs to reuse PCBs. When products like Large Household Appliances reach the treatment plant, PCBs are not extracted and therefore shredded with the whole device; for these reasons, the PCBs are recovered in debris together with other precious metals. In this case valuable materials and the above-mentioned components are lost in the fraction, since the recovery target query focuses mainly on precious metals. Moreover, due to the way the system is designed, it is not possible to conduct any analysis on the condition of the devices arriving at the treatment plant. As a result, it is not possible to determine whether the product is still functional or if any of its components are operational. Considering the state of art, reuse it is limited to local small-scale initiatives, especially focused on valuable components like GPU, CPU, RAM and other Laptop/Desktop components. Currently OEMs do not reuse circuit boards and/or their components in new products or as stock for spare parts, but according with new regulations in the EU panorama as per R2R and ESPR, the need to boost reuse of components is real and highly demanding, therefore it is of great interest investigating consolidated paths to assess if it is possible to rethink the extension of product or components lifecycle starting from the EoL environment .

5.2 Expected outcome

This pilot aims to improve the sorting of PCBs with the support of an AI classifier model and assessing the reusability or recyclability of electronic components. Specifically, the pilot will be supported by tailored digital tools developed as part of the CIRC-UITS digital toolbox to achieve the objectives of the two main streams in which the pilot is organized (Figure 24).

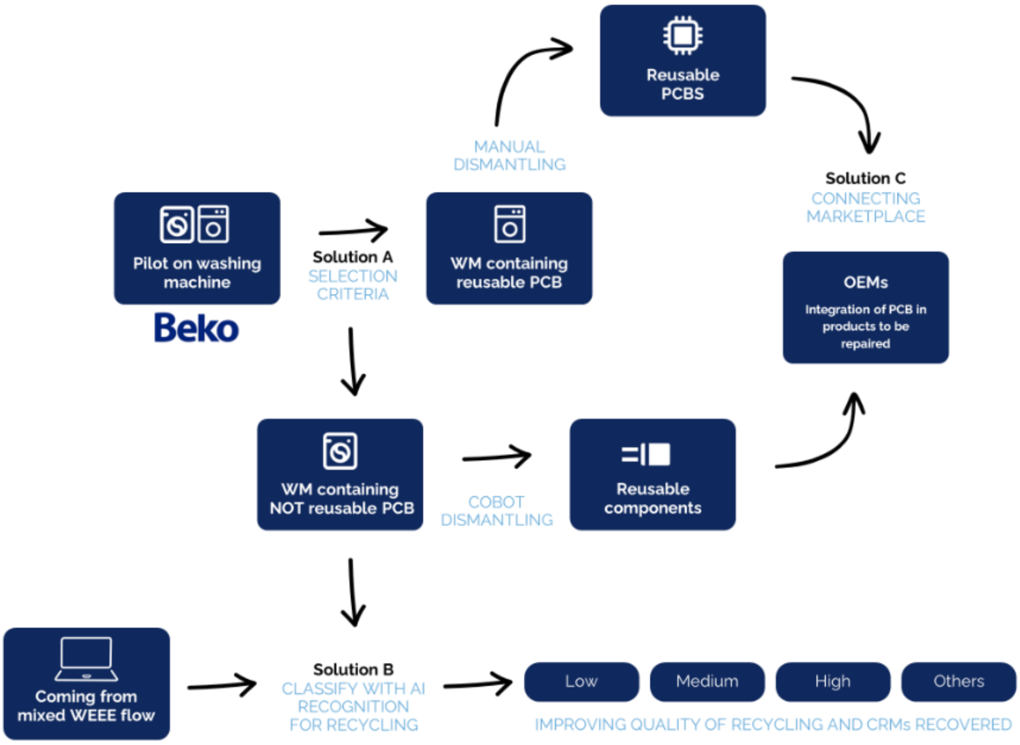


Figure 24: Pilot 4 scheme.

The first stream focuses on improving recycling efficiency to optimize the pre-treatment stage, leveraging AI image recognition. Improving the accuracy of the sorting by recognizing components on the PCB will possibly optimize the categorization of PCBs to better identify the most efficient recycling route and quantify the expected outcome. Hence, the pilot sets the basis, building on already consolidated practices of the treatment plant, aiming to detect components which serve as distinguishing features to determine the inclusion of the PCB in a specific category.

The second pilot stream focuses on evaluating the reusability of electronic boards and their components coming from EoL washing machines. As of today, the evaluation of sorting criteria and procedures aimed at identifying reusable PCBs is already an innovative aspect compared to the as-is situation. To define if a PCB is reusable or not, the first and main challenge is indeed to find in the waste stream the boards targeted by the producer. When it comes to the EoL sourcing a set of challenges need to be faced; most of the information that is hinged to labels and barcodes is not reliable because of the conditions of the aged devices and the impossibility to preserve the integrity of the devices from the collection point to the treatment plant route. To overcome this lack of information it is needed to consider different marks that might bring the research to the targeted element. Sourcing activities at the treatment plant require economic and resource efforts, therefore the research of a component needs to be settled on strong parameters; in the case of this pilot the PCB targeted was strategically chosen mainly for the following two reasons:

1. Availability of testing equipment for the manufacturer – specifically the accessibility of the firmware (FW) plays a crucial role during the testing phase because it is the embedded software that "communicates" with the hardware of the board to make it work
2. Statistically available sample – To ensure a profitable procurement campaign the most used model in the last 10 years was considered; according to Beko expected volumes in the field is in 2024 over 10M.

The pilot is therefore working on a specific digital tool that connects BoL and EoL actors (Marketplace tool), to boost and simplify the research. This marketplace is accessible through an HMI (Human-Machine Interface) system that can be used in mobility by the operator. To develop the connecting platform, it is important to consider both the best and the worst scenario in which the system might apply; the best scenario is considered as the availability of a barcode on the external case of the product; in this case by scanning the machine serial number, the system should be able to read all the info of the machine and therefore detect the presence of valuable and targeted components. The best-case scenario is also the less common scenario in which the HMI and the platform will be required to work. This scenario best applies if we consider using this application in different environments where the integrity of the product is maintained; perhaps the unsold items, stock leftovers, products withdrawn from the market, products returned by consumers due to warranty defects, and components replaced by service centers. The broader scope of operators and case study in which the system might apply make the tools future proof, despite this, the validation of the system will consider the worst, yet most realistic, of the scenarios considering the application field.

Since it is not a common operation to extract the PCBs from the Washing Machine in the pretreatment stages two different *modi operandi* are also considered to allow both treatment plant and manufacturer to adapt their needs to the potential of the platform. The first *modus operandi* is assuming that, because of the legislative panorama evolution, the request from the manufacturer for the sourcing of valuable components, will drastically increase in the next 10 years, requiring the whole EPR system and the treatment plant to rethink about collection and pretreatment stages, in this case for washing machine, but more in general for electronics and spare parts. With this hypothesis in mind, we can assume that treatment plants will be forced to extract PCBs and other specific components from all the machines to fulfill future market requests. With this idea it is possible to think that the easiest way for the treatment plants to, somehow, categorize and make available on the market the components will be to create a separate line for the registration of the components inside the Marketplace. What will be needed in this case is an AI recognition method, developed in the other pilot stream, which will support the sorting of the components, potentially by reading the marketplace query, detecting the selection criteria suggested by the manufacturer and the info on the PCB barcode. In this case as already mentioned some effort will be required from the treatment plant, first setting a new line independent from the treatment line, to categorize, store and ship the components, and more important establishing a warehouse to stock material waiting for manufacturer requests.

The second *modus operandi* is allowing the treatment plant to adapt in a more flexible way to the introduction of the digital platform, consider the idea to participate in occasional sampling campaign searching for components, by accepting a specific mandate established on the platform by a particular manufacturer.

The output of the second pilot stream will be the validation of the Marketplace tool, to enable manufacturers to browse components from the treatment plants to further test and potentially reintegrate it into new products. This is done to investigate a possible alternative supply stream for OEMs, considering that the manufacturer must provide spare parts to the customer for 10 years after the home appliance sale.

5.3 Defined targets

In summary, the pilot activities revolve around the validation of digital solutions that can support operators in the future during the sorting process by assessing the benefits in operational and economic terms. The use of an AI powered recognition model as well as the HMI visualization will assist the operators in the categorization of EoL PCBs for repair refurbishment and recycling, boosting new circular practices for the treatment plant and the OEMs. The following targets have been specified for the PCB sorting use case in Pilot 4:

1. Test at least 20 PCB to be reused;
2. 3 PCB classes will be developed in terms of image dataset (1000 images) for AR and AI-based tools;
3. Improve PCB sorting efficiency by 5%;
4. 5% of reusable PCBs reused from testing samples;
5. Demonstrate the technical feasibility of circular value chains;

5.4 Performed activities and current state of targets

To achieve the project goals, two parallel approaches are identified: the first focuses on automating the sorting process for PCBs within the facility; the second aims at assessing the feasibility of creating a market for refurbished components, starting from the identification and recovery of valuable parts from end-of-life devices within the treatment facility. Plans and goals were discussed, refined, and agreed upon in collaboration with all key technology partners from the pilot project, including BEKO, TXT, MARAS, and POLIMI. The following bullet list summarizes the main planned activities that are performed within the PCB use case:

- Definition of washing machine criteria selection to extract PCBs (target 1,5);
- PCBs reusability check from OEMs (target 1, 4,5);
- Marketplace of reusable PCBs definition (target 1,4,5);
- Validation of selection criteria (iterative approach) from different sources (target 1,5);
- Study of as-is PCBs manual sorting (including collection of 1000 PCBs photos as inputs to AI algorithm) (target 2,3);
- Supporting AI-based camera development and validation (target 2,3);
- Economic evaluation of PCBs improved sorting and recyclability (target 3).

5.4.1 Automation of the sorting process

For the automation of the sorting process, in collaboration with the selected treatment plant, three PCB classes were developed based on the PCB's economic value.[2] This value is defined according to the treatment plant internal strategy, developed over the years and based on the results of smelters' economic assessment and samples analysis. The method is based on the operator's capability to recognize specific components and precious materials content of PCBs. The classification based on the learn by doing method of the treatment plant was further validated by comparing it with different treatment plants' strategies as well as the smelters perspective provided by MARAS. It was indeed crucial to understand the strategy of the treatment plant for the recognition of the PCBs categories because it allowed us to structure a set of features and define a suitable training dataset to build a solid AI recognition model.

The three categories, based on the material that the treatment plant is collecting, are:

- **First choice boards**
  - Hard disk boards:
    - Example products: Internal and external hard drives, SSD and HDD storage units.
  - Mobile phone boards:
    - Example products: Old-generation mobile phones (TACS).
  - Super Back Panels first choice boards:
    - Example products: Telecommunication equipment, telecom cabinets.
  - Super OT first choice boards:
    - Example products: Telecommunication equipment, optical transmission devices, fiber optic network equipment.
  - Super peripheral first choice boards:
    - Example products: Older generation personal computers.
  - High yield boards:
    - Example products: High-end devices such as workstations, high-end servers, medical and scientific equipment, flat-screen TVs (limited to screen management components), industrial devices, laptops, old video game consoles.
  - Super first choice boards:
    - Example products: Servers, mainframes, network devices, industrial equipment, new game consoles, slot machines.
  - First choice old-generation boards:
    - Example products: Old desktop and laptop computers.
  - First choice of new-generation boards:
    - Example products: Modern laptops and desktops.
- **Second choice boards**
    - Example products: Video cameras, mid-range devices, smartphones, industrial equipment.
- **Third choice boards**
    - Example products: Low-end home appliances, small electronic devices, low-end electronic gadgets, power supply boards, power boards.

[2] Information on the classification methodology is provided in ANNEX B – "PCBs categories – CRMs" and ANNEX C – "PCB categories identification strategy and tips".

For the AI training 2 datasets of pictures of PCBs were collected: the first dataset included 1000 photos, of which 100 were of HDD boards divided by value and age (see Figure 25 left). These 100 photos were used as a small-scale proof of concept that allowed TXT to evaluate challenges and issues with the recognition model, enabling improvements in the system.

Subsequently the remaining photos of first, second and third category were randomly selected according to the treatment plant availability (see Figure 25 right). The second dataset was structured differently, including photos of all the categories to increase the model classification capability. This set contained 210 first-choice, 295 second-choice and 495 third-choice photos.

Figure 25: Left. batch of HDD PCBs collected during the first round of data gathering. Right. HDD PCB boards divided by year (from left to right, oldest to newest).

The study of PCBs manual sorting functionally supported the training of the AI based model, which will be tested in the treatment plant throughout 2025, to assess how the synergy with technologies can improve the accuracy of the process, providing a much more reliable sorting method for the treatment plant, and paving the way towards a future system to support the detection of CRMs content that will become a mandatory output of the recovery process as defined from the EU legislative panorama. The test will evaluate the AI-based model performance in the treatment plant environment allowing the comparison between the manual sorting and the digital one. The AI based model is designed to support the extraction line for circuit boards, enabling them to be assessed and potentially reused in new products. Considering full-scale operations where operators will not only select washing machine boards but may also integrate their search tasks into the pretreatment and sorting phase preceding mechanical processing, it is clear that alongside finding viable boards, they will also need to classify those to be discarded and sent for treatment.

In this context, the AI model simplifies the information load that operators would otherwise need to process and manage. Imagine the effort required to determine whether the board in your hand is the target one for placement on the marketplace or if it should be sent for treatment—and, if so, into which category it should be classified. The AI model serves as an invaluable tool in streamlining this process.

5.4.2 Reuse of refurbished components

To discover the potential of establishing reuse and repair practices for OEMs, starting from Large Home Appliances at their EoL stage, some criteria to detect valuable components had to be settled. Different approaches were evaluated together with the Manufacturer BEKO Europe and the treatment plant involved.

Beko selected as a target for the PCBs known as 'Windy Strip BPM' and 'Windy Strip UM'. This Windy Strip BPM (shown in Figure 26) is the in production since 2015 and it was selected as it is in production with very high volumes (estimated production per year is over 1 million of boards and estimated volumes of this PCB in the market is over 10 million). According to BEKO this should significantly increase the probability to find it in the dismantling plant.

Figure 26: Targeted PCB known as Windy Strip BPM

The selection fulfils the need to have suitable testing tools to assess whether or not the PCBs can ensure performance compliance with specific parameters for the reintroduction into new products. Once the targeted PCB was identified, a list of criteria depending on the PCB characteristics was drafted to enable the research at the EoL treatment plant; BEKO demanded for the detection of the Machine serial number (Figure 27 left) to extract the year of production (put on market year POM), being no more than 5 years back in the days (POM year >2018).

Figure 27: Left. Washing machine serial number. - Center. PCB serial number – Right. Connector on the rear of the appliance

Together with the treatment plant and the Manufacturer a third criteria was added in order to assist the activities at the treatment plant, requiring the detection of the specific beige colour and presence of the connector in the rear part of the machine (Figure 27 middle). Finally, a verification of the PCB serial number (Figure 27 right) was conducted as the final step to determine whether the PCB was the targeted one.

The Windy Strip BPM PCB can be easily identified by the label on its plastic housing, (see the red rectangle in Figure 28 below) which clearly indicates the hardware (HW) and software (SW) versions of the board. However, since the practice of extracting the PCB is not yet well-established in the EoL practices, an additional step was necessary to identify, from the outside, the machines that might potentially contain the targeted PCB.

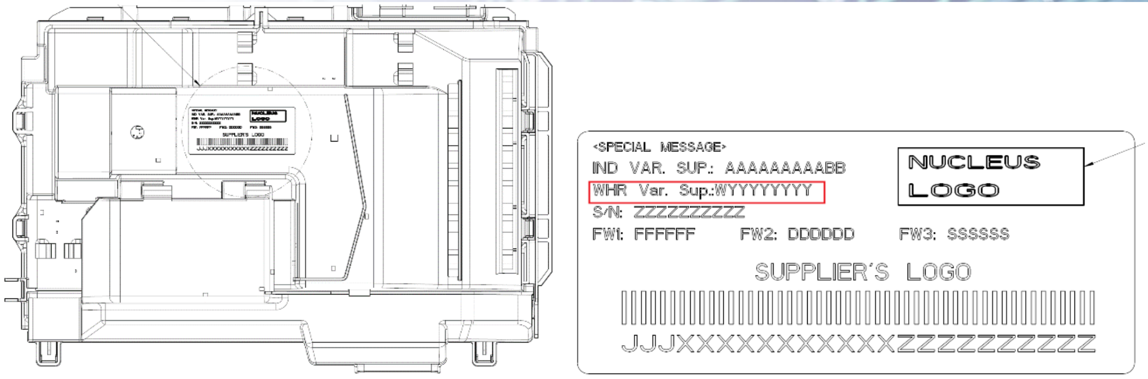
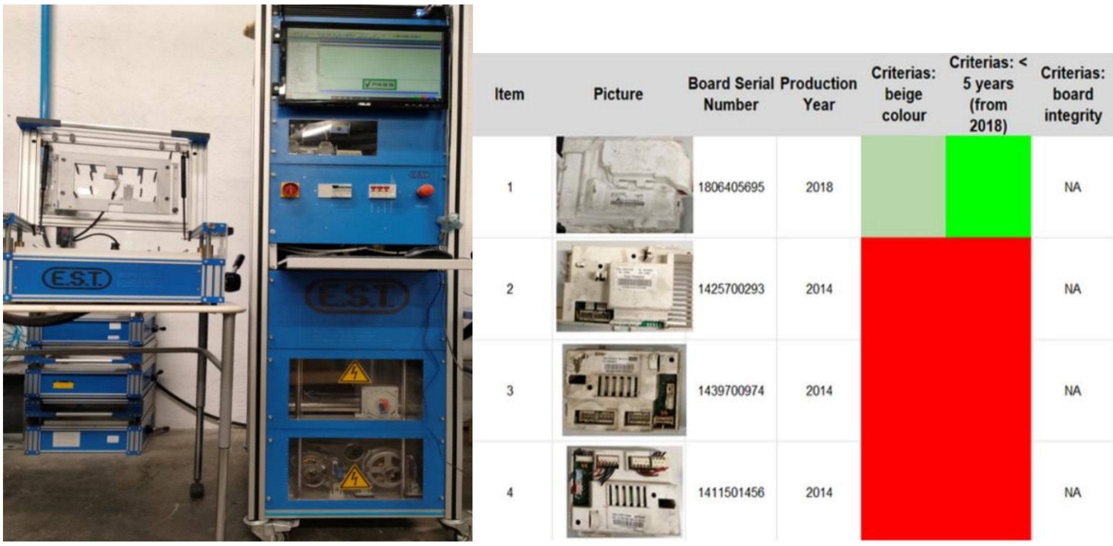


Figure 28: Plastic housing indicating the hardware (HW) and software (SW) versions of the board.

The outcome from the first batch evaluation showed that it was quite challenging to meet the targets. The objective was to find at least 20 PCBs of interest to be tested from BEKO, but from a sample of 40 washing machines, only 5 PCBs satisfied the requirements provided by the manufacturer. The selected PCBs have been sent to Beko to proceed with a deeper functional analysis. Beko executed a functional automated test on the received parts to verify the proper functionality of the boards. (Figure 29)

The Automated Test Equipment (ATE) test consists of performing a function test of the board sending over the communication bus commands to activate loads and read sensors input. The outcome of the test is that 4 PCBs have been found as acceptable, while 1 PCB did not pass the test.



Item	Picture	Board Serial Number	Production Year	Criterias: beige colour	Criterias: < 5 years (from 2018)	Criterias: board integrity
1		1806405695	2018			NA
2		1425700293	2014			NA
3		1439700974	2014			NA
4		1411501456	2014			NA

Figure 29: ATE test equipment and test results report extraction.

For this reason, the decision has been made to revise the PCB criteria and perform a second round of assessment. For this second analysis, therefore, the washing machine code number was also considered (see red rectangle in Figure 27 left). According to the manufacturer, it is possible to detect a pattern in the code number of the washing machine by consulting the internal company database. The WMcode number consistently appears in four distinct patterns, each containing eleven characters and digits. It can be formatted as a code starting with "W" followed by eleven digits, or as codes starting with "75," "76," or "72," each followed by 10 digits. (Figure 30) Thanks to this pattern, the detection of the targeted PCBs could be guaranteed reliably. With this knowledge and considering that the targeted PCBs have been installed in more than 500 different models, a new round of inspection has been initiated, this time targeting a batch of 100 appliances to be analysed. The primary task for the operators was to identify this code on the exterior of the washing machine and communicate it to the manufacturer, who was expected to confirm whether the machine contained a targeted PCB. Unfortunately, the time required for the manufacturer to verify the WMcode was not instantaneous, disrupting the normal workflow of the treatment plant.

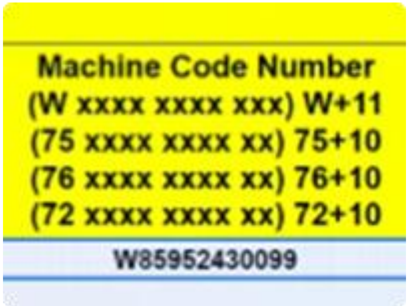


Figure 30: WM code number pattern for the detection of the targeted PCB in the Manufacturer database.

It is important to notice that the newly defined criteria were initially excluded due to the condition in which the WM reached the first treatment plant (see Figure 31). Furthermore, even if the condition of the WM reaching the second treatment plant seemed promising, the above-mentioned criteria had to be dropped, as it was considered disruptive in the working flow. Unfortunately, the outcome of the second batch analysis could not provide enough material for testing. Indeed, a batch of 1000 washing machines was analyzed in 2 months and as a result only five potential PCBs were obtained, of which only two resulted in target. The selected PCBs have been sent to Beko to proceed with a deeper functional analysis. Beko is going to analyse the PCB (ATE test) to check if the 2 boards received can be considered acceptable from a functional standpoint.

Figure 31: Washing Machine condition at the first treatment plant involved in the scouting of PCBs.

5.5 Innovative aspects compared to SOTA

- Integration of advanced digital tools, specifically an AI classification model, to evaluate and categorize PCBs based on their economic value. This AI-driven approach significantly increases the accuracy and efficiency of sorting operations, transforming a traditionally manual process into an automated, optimized system, and is therefore considered a key innovation aspect.
- Development of a digital circular marketplace. This tool connects OEMs with Waste Electrical and Electronic Equipment (WEEE) treatment plants, facilitating the exchange and reuse of sorted PCBs. By providing a centralized system for sharing information about reusable PCBs, this marketplace promotes a circular economy within the industry, boosting reuse among the whole value chain and ensuring compliance with ever-demanding EU regulations in terms of material and components recovery. Due to the novelty of the proposed solution, this is also a key innovation aspect.
- Establishment of detailed criteria for the detection of PCBs that might be reused and criteria for PCBs sorting. By defining parameters for selecting End-of-Life (EoL) washing machines that may contain reusable PCBs and conducting practical assessments, the project ensures that only high-quality PCBs are selected for reuse; such parameters and, in general, the considerations made by the pilot allows it to be replicable. This systematic approach represents a significant step towards a more sustainable electronic waste management.

5.6 Plans for the next phase

To complement the initial findings and results obtained from PCBs sorting activity in EoL, some consideration on the lifecycle of the Large Household Appliances (LHA) must be made. First, the pilot will further investigate the tools at disposal of the manufacturer to understand what might be needed to open the scope to different PCBs models and allow manufacturers willing to enable reuse and repair practices to get equipped with proper testing toolkit. Secondly, the pilot will investigate different waste streams to try and detect whether it is possible to access EoL WM from unsold goods, damaged LHA and different grouping facilities. By mapping the waste streams, the pilot will work on waste flow prevision to understand the proportion of the targeted PCBs in the upcoming future. Considering that a washing machine lifespan ranges from 7 to 14 years, it is possible that the targeted PCBs are still too young to be found in the treatment plant nowadays. To validate the idea of developing the Marketplace channel and connecting OEMs and treatment plants, the PCBs found will be tested and the interest of different stakeholders will be considered in a set of interviews, also with a view to determining which exploitation plan to adopt in collaboration with TXT.

For what concerns the sorting automatization the training of the AI classification model will be finalized and the validation test in the treatment plant will be organized together with TXT. Together with MARAS insights for the optimization of PCBs sorting, based on detailed metallurgical knowledge, will be provided.

6 Visual inspection, disassembly and remanufacturing activities

POLIMI is automating the remanufacturing of electronic components, focusing on materials from partners involved in piloting activities (e.g. BOSCH, CONTINENTAL, BEKO and TNO). These activities explore robotics, automation and machine learning to automate tasks traditionally done by skilled labor. Initially, feedback from manufacturers will define disassembly targets and materials, followed by selecting and testing appropriate tools in POLIMI's Industry 4.0 Lab. Manual disassembly tests will identify issues and refine strategies, with components sent back to partners for functionality testing. A closed-loop feedback process will optimize procedures, and machine vision solutions, where possible, will be developed for greater flexibility in identifying and disassembling components.

6.1 Methodology

Precision robotics play a critical role in facilitating the precise separation of delicate components, thereby optimizing the remanufacturing workflow. This research advances beyond conventional manual testing methods by incorporating closed-loop feedback mechanisms, which enhance both flexibility and accuracy while reducing reliance on skilled labor. The transition towards automation fosters a more sustainable and economically viable remanufacturing process. By integrating these advanced technologies, the study aims to transform POLIMI's remanufacturing operations, establishing a new benchmark for future initiatives in the electronic manufacturing sector. The methodologies developed through this research are designed to significantly improve the precision, efficiency, and sustainability of remanufacturing practices, aligning with the broader objectives of Industry 4.0.

To achieve these advancements, a specific model was developed to enable closed-loop feedback in collaboration with the manufacturers of the tested circuit boards (Figure 32). This approach was necessary, as testing activities on disassembled components require access to proprietary hardware and software resources available only to the manufacturers, enabling accurate verification of component status. The workflow begins with a comparative analysis conducted in partnership with OEMs. This step is crucial for identifying the target components to be remanufactured and involves collaboration with experts who possess a comprehensive understanding of the product's functional and economic aspects. During this phase, critical information is gathered regarding the components' assembly techniques and disassembly guidelines, establishing operational parameters such as allowable temperature limits and ramp profiles to ensure safe handling of the components.

Figure 32: The workflow adopted for the remanufacturing activities.

Following the initial data collection, manual disassembly tests are conducted to assess the feasibility of the remanufacturing process. These tests identify potential disassembly challenges by employing various precision tools and methodologies to optimize component removal. At this stage, preliminary feedback is gathered from manufacturers by submitting the disassembled materials for functionality testing. Additionally, the potential application of AI-based solutions for identifying target components is evaluated. This step is considered optional, depending on the specificity of the targeted components. For components unique to a particular PCB layout, the value of an autonomous identification system is limited. Conversely, for generic components found across multiple PCB layouts, developing such a system may be advantageous. However, the feasibility of these solutions hinges on the availability of detailed training data, which is often inaccessible or insufficient. The final stage involves the development of a proof of concept for an automated component removal system. This phase focuses on prototyping custom end effectors for component extraction, which are designed in collaboration with external partners and manufactured using additive manufacturing techniques. The iterative process involves evaluating the prototypes, gathering feedback from manufacturers, and refining the design to optimize functionality. Additionally, a comprehensive analysis of available technologies is conducted to determine the most suitable equipment required for the system.

6.2 Use cases

This section reports the activities of the various case studies parallel to the pilots.

6.2.1 Pilot 1: Bosch ECU

Upon receiving the materials from Bosch, consisting of PCB boards extracted from ECUs encased in plastic housings, we collected the manufacturer’s input regarding the target components for removal and the recommended disassembly procedures. The supplied ECU boards featured four distinct layouts and contained various types of electronic components. The integrated circuits (ICs) on the ECUs were identified as the primary targets for removal, as they represent the most valuable components on the board. To streamline preliminary operations, the focus was limited to larger components. The objective was to remove these components while preserving the integrity of both the components and the source boards. For soldering and desoldering, the JEDEC J-STD-020D.1 standard was followed, which specifies maximum allowable temperatures and temperature ramp limits to prevent thermal shock. Bosch also recommended the use of air ionizers during disassembly to mitigate the risk of static electricity damaging the boards. After aligning with Bosch on the disassembly process, initial manual disassembly tests were conducted to evaluate the suitability of various tools for the remanufacturing tasks. These tests were essential for defining the actuators required for automated component removal. Tool performance was assessed based on disassembly speed, stress on the components and boards (monitored through temperature measurements), and the visual condition of the parts after disassembly. The target components, all belonging to the category of integrated circuits, included two configurations: Ball Grid Array (BGA) and Quad Flat Pack (QFP). Based on the board layout, a hot air desoldering tool was selected for disassembly. The disassembly process differed depending on the component type: QFPs were heated directly using a focused hot air stream, while BGAs were heated from the backside of the board to achieve more uniform heat distribution. Each method had its trade-offs: direct hot air application enabled faster disassembly but increased the risk of thermal damage, while heating from the backside provided a gentler temperature gradient but required more time and occasionally desoldered unintended components. Thermocouples were used during all tests to monitor temperature trends in real time. Once the components were removed, they were sent to Bosch for functionality testing. The layout of the boards presented challenges due to the high density of components, which sometimes obstructed the placement of heat sinks and led to the unintended disassembly of adjacent non-target components. Additionally, difficulties in positioning heat sinks complicated the alignment of component extractors. This issue was particularly pronounced for BGAs, where solder occasionally spread over the component surface during removal, necessitating cleaning before retesting. Following manual disassembly, the components were sent back to Bosch for functional testing, but it was found that due to the encryption of the components, testing would not be possible. Therefore, it was decided to change the ECU board and the target component of the remanufacturing activities. The new ECU will be subject to the testing of the automated procedure (Figure 33).

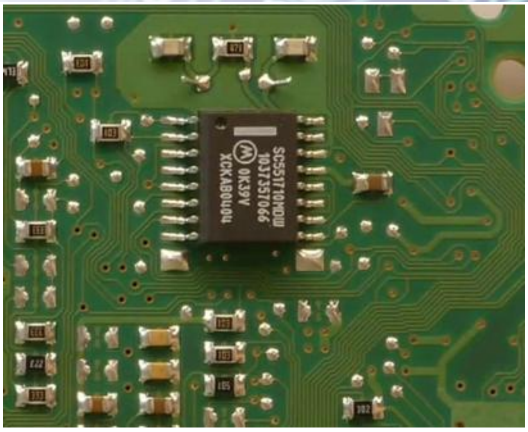


Figure 33: Target component.

In parallel with the disassembly activities, a computer vision-based solution was developed to identify the target components. Since the targets were exclusively integrated circuits, a neural network was designed to recognize and locate them on the PCBs. To train this network, the WPCB-EFA dataset (C. Pramerdorfer et al., 2015) [3] was selected. This dataset contains 748 PCB images from a recycling facility, along with accurate segmentation and bounding box annotations for 9,313 integrated circuit samples. Given the complexity of using Convolutional Neural Networks (CNNs) for recognizing electronic components, the YOLOv5 model was chosen. Transfer learning was applied to the final layers of the network to tailor it to the specific requirements of this application. This approach leveraged the pre-trained layers of YOLO, which are optimized for recognizing basic features, while training only the final layers for high-level classification tasks. This methodology proved effective, enabling high performance even with a relatively small training dataset. After training, the model was tested on the ECU boards and successfully identified all but one target component (Figure 34). The unidentified component, a next-generation integrated circuit with a visually distinct design, fell outside the scope of the training dataset. To address this, a supplementary approach using conventional computer vision techniques was implemented. By isolating the component's unique orange frame—a distinguishable feature against the board's background—its position was successfully identified using a color-tracking algorithm. The combination of these solutions marked the development of the first automated component of the system, enabling precise identification of target components. The flexibility of the proposed solution enables its application not only in the Bosch case but also for Beko's washing machine boards.

[3] C. Pramerdorfer and M. Kampel, "A dataset for computer-vision-based PCB analysis," 2015 14th IAPR International Conference on Machine Vision Applications (MVA), Tokyo, Japan, 2015, pp. 378-381, doi:10.1109/MVA.2015.7153209.

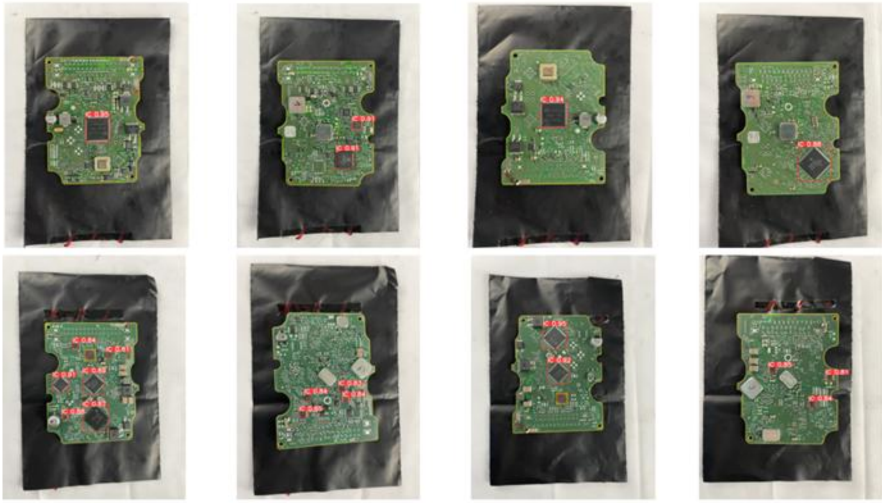


Figure 34: Red bounding boxes around Identified ICs.

To further enhance the adaptability of the solution, an additional component has been integrated, allowing for the identification of specific integrated circuits (ICs) based on their labelled characters. This functionality is currently undergoing testing, but preliminary results are highly promising due to the robust capabilities of Vision-Language Models, which provide significant flexibility and accuracy.

6.2.2 Pilot 2: Continental In-Tire-Sensor

The remanufacturing project for the Continental In-Tire sensor was undertaken to investigate the feasibility of reworking and reusing components within automotive sensor systems, emphasizing sustainability and cost-effectiveness in the automotive sector. The study focused on assessing the potential for disassembling and reworking specific sensor components, particularly the PCB. A complete disassembly of the sensor was performed, yielding a preliminary mass balance that detailed the breakdown of its components. The sensor's initial weight was measured at 1.46 grams, with the disassembled PCB accounting for 0.96 grams of the total mass. This process revealed significant challenges associated with the disassembly of smaller components, which were pivotal in evaluating the remanufacturing potential. The disassembly challenges posed by smaller components highlighted limitations in feasibility. The PCB's intricate and delicate structure required meticulous handling, suggesting that reworking or repairing smaller components may not be practical. Manual disassembly methods were employed to establish optimal procedures for potential automation (Figure 35). These manual methods were critical due to the sensor's compact size and the complexity involved in detaching components without causing damage. Specialized precision equipment was utilized to facilitate the removal of candidate components for rework. Despite rigorous testing, the remanufacturing process for the Continental In-Tire sensor was ultimately found to be complex.

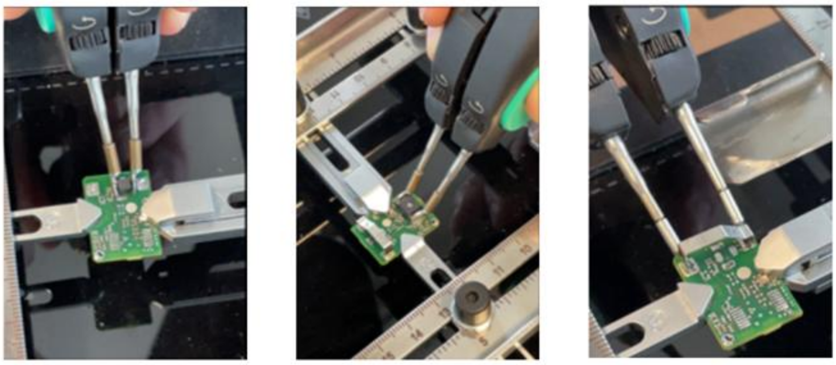


Figure 35: Disassembly of components from the PCB.

The primary challenges identified included:

- **Component Size**: The small size of certain components made them difficult to handle without damaging adjacent parts.
- **Complexity of Automation**: The intricate and sensitive nature of the disassembly process rendered automated remanufacturing tasks impractical.

In consultation with Continental, it was determined that continuing the project was infeasible under current technological and resource constraints. The findings underscore the inherent difficulties in remanufacturing complex automotive sensors like the Continental In-Tire sensor. While larger components, such as the PCB, may theoretically be suitable for rework, the technical complexity and practical limitations associated with smaller parts present significant barriers.

Future research and development in this domain may focus on the following areas:

- **Enhanced Automation Tools**: Developing specialized machinery capable of handling small and delicate components with greater precision.
- **Component-Level Design Optimization**: Redesigning sensors to incorporate modular components, enabling easier disassembly and reassembly.
- **Material Recycling Alternatives**: Exploring efficient recycling methods for sensor materials as a sustainable alternative if remanufacturing proves unviable.

The decision to suspend the remanufacturing efforts highlights the pressing need for advanced technologies and innovative approaches to support sustainable practices in automotive sensor remanufacturing.

6.2.3 Pilot 3: Green IME

The design and disassembly of IME components are integral to advancing sustainability in modern manufacturing, particularly through remanufacturing and recycling initiatives. This section explores quality control methodologies in the context of IME disassembly, with a focus on leveraging visual inspection technologies to enhance the accuracy and efficiency of the process. A structured approach to disassembling IME components is developed, emphasizing rigorous quality control to identify faults or defects that may arise during disassembly and impact the remanufacturing potential of these components. Central to the proposed methodology is the utilization of advanced visual inspection technologies capable of finding defects such as circuitry damage and missing or absent critical components (see Figure 36).

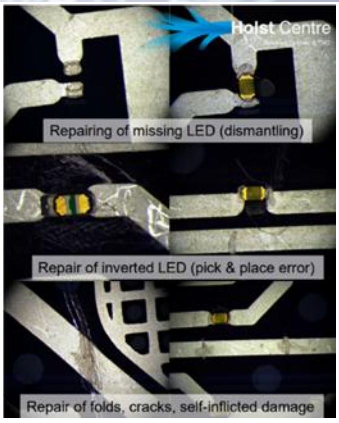


Figure 36: Catalog of various possible defects.

Among the tools investigated is a state-of-the-art smart camera system renowned for its high precision in surface defect detection and its ability to verify the presence of essential components. Feasibility studies conducted in collaboration with the smart camera provider focused on evaluating the system's capabilities, particularly in detecting missing LEDs—a common defect during disassembly. These studies demonstrated the system's potential, with the successful identification of missing LEDs marking a significant milestone in validating the technology's applicability to IME disassembly (Figure 37). The initial focus on LED detection represents the foundation of a broader quality control strategy. Future research will aim to extend these capabilities to identify additional defects, such as surface scratches and errors arising during automated pick-and-place operations. Addressing potential misalignments or deformations of components due to thermal cycling will also be a priority.

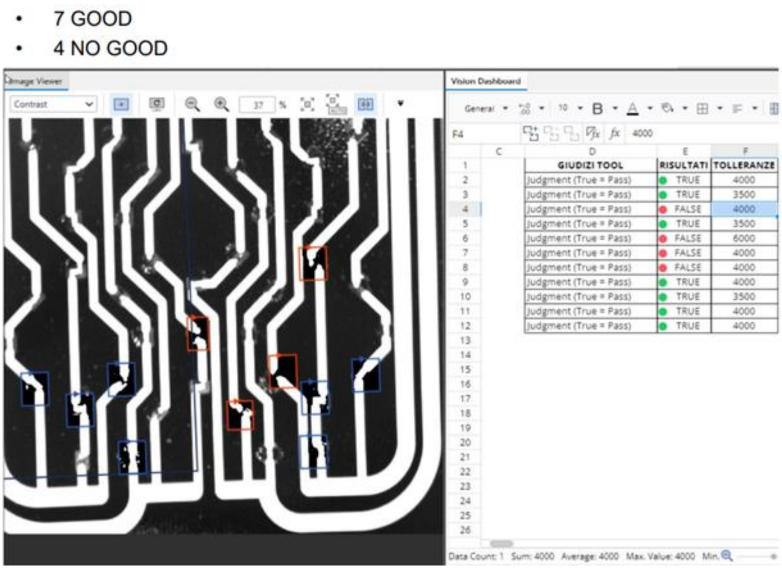


Figure 37: Outcome of the missing components assessment. The red (missing component) and blue (component) squares on the left image are the areas of inspection.

The smart camera system employed in this study exemplifies innovative advancements in visual inspection, featuring adaptability to diverse inspection needs within automated environments. These systems utilize sophisticated algorithms to detect minute defects that may elude manual inspection, allowing for the establishment of multiple inspection zones per component. Real-time analysis and immediate fault detection are particularly beneficial in complex manufacturing environments, where maintaining production quality and minimizing delays are critical.

Despite the promising results of the feasibility study, several challenges must be addressed for the broader implementation of this technology:

- **Surface Defect Detection**: Further refinement of the smart camera algorithms is necessary to accurately identify subtle defects, such as surface scratches, which are more difficult to detect than missing components.
- **Pick-and-Place Errors**: Integration of visual inspection into automated pick-and-place systems presents challenges, particularly in detecting errors related to thermal cycling-induced deformation of the printed foils. Identifying such errors is vital for ensuring the proper assembly of remanufactured components.
- **Scalability**: Expanding the deployment of smart camera systems across a full production line involves both technical and economic considerations. Additional research is required to evaluate the cost-effectiveness of large-scale implementation.

The adoption of advanced visual inspection technologies represents a significant step forward in enhancing quality control for the disassembly and remanufacturing of IME components. The successful detection of missing components, such as LEDs, highlights the potential of smart camera systems to streamline disassembly processes. Future work will aim to refine these technologies for the detection of more subtle defects, ensuring their long-term effectiveness. By improving quality control during disassembly, this approach supports more sustainable manufacturing practices, aligning with the increasing demand for re-manufacturable and recyclable electronic components.

6.2.4 Pilot 4: BEKO washing machine PCB

The remanufacturing project for BEKO washing machine PCBs was initiated to develop effective strategies for the recovery and reuse of components, with the overarching goal of promoting sustainability and reducing electronic waste in the home appliance industry.

The study focused on the disassembly of Surface-Mounted Device (SMD) components, with particular emphasis on components labeled QD2 and QD5, which were identified as key candidates for potential reuse and remanufacturing (see Figure 38). Initially, the scope of target components was broad, complicating the disassembly process. By narrowing the focus to specific components such as QD2 and QD5, the project sought to improve the efficiency and success rate of recovery efforts.

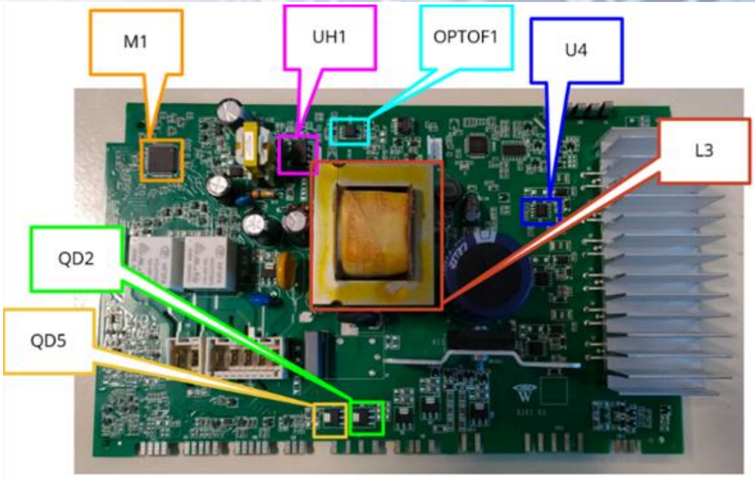


Figure 38: The washing machine PCBs and the initial target components

Multiple disassembly tests were conducted using various types of equipment, including:

- **Custom IC Desolderer**: Used for the precision removal of integrated circuits from the PCB.
- **Air and Heat Sink Combination**: Tested to evaluate its effectiveness in minimizing thermal damage during disassembly.

The disassembly process highlighted several challenges, particularly during the removal phase. Residual solder paste, especially around the pins of the components, frequently impeded clean removal. To address this issue, a specialized component extractor was employed, which enhanced the quality of removal and improved operational efficiency (Figure 39). However, this solution also introduced additional complexity to the automation of the process. The presence of residual solder paste underscored the need for more advanced extraction techniques to streamline disassembly.

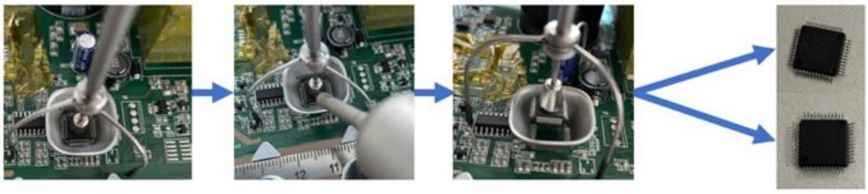


Figure 39: Results of the two preliminary disassembly methods.

To address the challenges of automation, a custom end-effector, originally developed for Bosch ECU target components, is being assessed for its applicability in automating the extraction of Whirlpool washing machine PCB components. This tool is expected to provide insights into the feasibility of scaling automated disassembly processes.

The findings from this project underscore several critical points:

- **Complexity of SMD Removal**: While manual disassembly was effective, it revealed difficulties associated with residual solder paste. Automating the process will require advanced equipment capable of addressing these challenges.

- **Component-Level Testing**: The evaluation of specific end-effectors for automated disassembly could significantly improve the feasibility of large-scale remanufacturing.
- **Sustainability Implications**: The successful remanufacturing of washing machine PCBs aligns with sustainability goals by reducing electronic waste and conserving resources.

Future recommendations include exploring advanced desoldering methods and further refining automation tools to manage the specific challenges of component disassembly. By optimizing these processes, BEKO can enhance its remanufacturing capabilities, contributing to greater sustainability and resource efficiency in appliance manufacturing.

6.3 Proposed automated solution

The process incorporates advanced technologies and methodologies aimed at achieving efficient disassembly while monitoring key metrics (Figure 40).

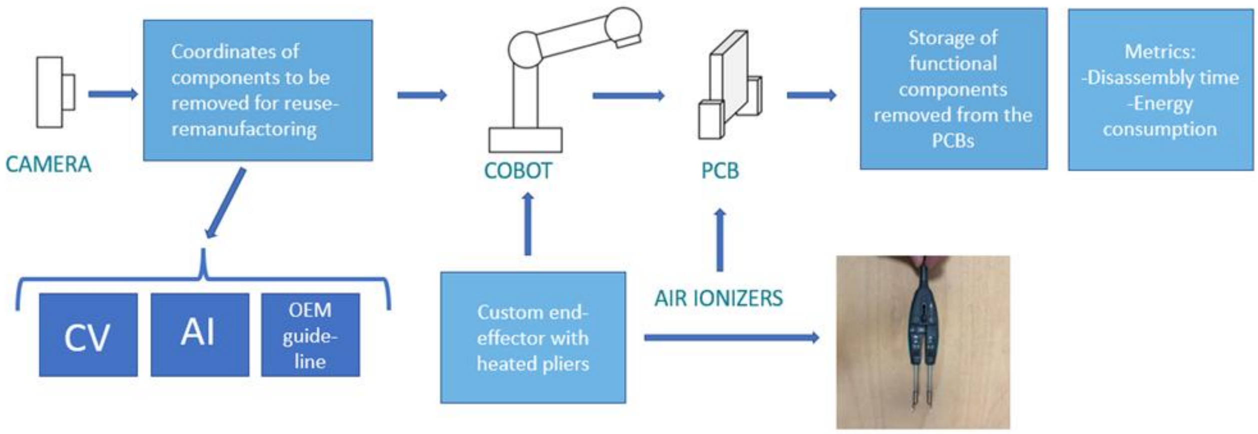


Figure 40: Proposed framework for the pilot plant dedicated to remanufacturing activities.

1. **Camera Integration**: A vision system captures the image of the PCB to identify and locate components to be removed. This is achieved through computer vision (CV), artificial intelligence (AI), and adherence to OEM guidelines. The generated coordinates guide the subsequent steps in the disassembly process.
2. **Custom Cobot End-Effector**: A collaborative robot (Cobot) equipped with a custom-designed end-effector featuring heated pliers is used to delicately extract components. This ensures minimal damage and thermal shock to the components and facilitates their reuse or remanufacturing.
3. **Use of Air Ionizers**: Air ionizers are employed to neutralize electrostatic charges on the PCB surface, preventing potential damage to sensitive electronic components during handling.
4. **Storage and Metrics Monitoring**: Once removed, functional components are stored for future reuse. The system also tracks critical metrics, including disassembly time and energy consumption, to evaluate the process's efficiency and environmental impact.

This modular and intelligent framework provides a robust solution for sustainable electronics recycling and circular economy initiatives.

The primary function of the custom tool is to enable the robot gripper's stroke to control the closing mechanism of the thermal gripper, ensuring precision and reliability in component handling.

1. **3D Scanning for CAD Generation**: The development process begins with 3D scanning of the thermal gripper. This scanning provides accurate geometric data for the creation of a computer-aided design (CAD) model.
2. **Mechanical Design of the Structure**: Based on the CAD model, a mechanical design is created. This step focuses on ensuring that the custom tool fits within the robot gripper while maintaining the required functionality and structural integrity.
3. **Realization via Additive Manufacturing**: The structure is fabricated using additive manufacturing techniques, specifically with PA-12 (polyamide) material. This material is chosen for its strength, durability, and suitability for precise mechanical applications.
4. **Testing and Validation**: The final step involves rigorous testing and validation to ensure the tool meets the functional and operational requirements. This stage verifies the integration between the robot and the thermal gripper, ensuring smooth and reliable operation.

This structured development approach highlights the integration of advanced manufacturing technologies and design methodologies to enhance robotic functionalities for industrial applications.

6.4 Conclusions and future work

This study presents significant advancements in the automation of electronic component remanufacturing, driven by collaborative efforts between POLIMI and industrial partners like BOSCH, CONTINENTAL, BEKO, and TNO. By integrating precision robotics, machine vision, and feedback-driven methodologies, this research addresses the challenges associated with traditional manual disassembly processes. The developed solutions showcase the feasibility of achieving higher precision and efficiency while aligning with the principles of Industry 4.0 and sustainability. The use case pilots underline the complexity of remanufacturing tasks across diverse electronic systems. Key findings from these pilots highlight the importance of customized tools, AI-based recognition systems, and advanced methodologies to overcome challenges such as thermal management, component identification, and intricate PCB layouts. While some remanufacturing efforts, such as the CONTINENTAL In-Tire sensor project, were deemed infeasible under current constraints, the study’s successes in other domains, including automated identification and disassembly of integrated circuits, demonstrate promising pathways for scaling these technologies. Moreover, the proposed framework for automated remanufacturing reflects the potential for modular and scalable solutions capable of adapting to various industrial contexts. This study establishes a robust foundation for future advancements in electronic waste reduction and sustainable manufacturing practices.

The next steps in this research will focus on the testing and validation of the proposed automated remanufacturing system and the further development of advanced inspection technologies for printed electronics.

1. **Testing of the Proposed Automated System:**
   - The modular framework for automated disassembly will undergo rigorous testing to evaluate its performance under real-world conditions.
   - Key metrics, such as disassembly accuracy, processing time, energy efficiency, and the integrity of recovered components, will be monitored and optimized.
   - Feedback from these tests will inform iterative improvements in the system's design, particularly the performance of the custom Cobot end-effector and its integration with vision-based guidance.
2. **Advancement of IME Inspection Technologies:**

- Research efforts will concentrate on refining smart camera systems for enhanced detection of defects and missing components in disassembled IMEs.
- The current capabilities, focused on LED detection, will be expanded to include more subtle faults, such as surface scratches and thermal deformation, ensuring comprehensive quality control during disassembly.
- Scalability and adaptability of the inspection technology will be evaluated, including integration with automated pick-and-place systems and other industrial applications.

By concentrating on these next steps, the research aims to validate the feasibility of the automated remanufacturing process while ensuring its adaptability to complex and diverse electronic systems. These efforts will pave the way for industrial-scale adoption of sustainable practices in electronic component remanufacturing.

7 Implementation of Digital Tools and Advisory

7.1 Digital tools

Digital tools allow for uses that pure technical analyses cannot cover. They can connect different data sources and generate knowledge based on the available information that is relevant to the user. This is one of the advantages of the digital tools that are provided and developed in the CIRC-UITS project. The digital tools come together in the form of the CIRC-UITS Digital Toolbox which encompasses a series of modular, highly interoperable components that are designed to be easily integrated within existing pilot streams, supporting various kinds of activities and covering all aspects of the product lifecycle. Table 3 shows how each pilot is exploiting the Digital Toolbox. Further details for each module are provided throughout the rest of this chapter.

Table 3: CIRC-UITS Digital Toolbox components mapping for each pilot.

PLATFORM COMPONENTS USAGE					
COMPONENT	**Involved tech partner**	**Pilot 1 - BOSCH**	**Pilot 2 - CONTI**	**Pilot 3 - TNO**	**Pilot 4 - ERION**
Advisory	SUPSI/OFFIS	x	x	x	x
Advanced HMIs	TXT				x
LCS&CA	SUPSI/MARAS	x	x	x	
Marketplace	TXT				x
Digital twin (DT)	OFFIS	x	x	x	
Data Layer	TXT	x	x	x	x

One of the tools mentioned is the Digital Twin, developed by OFFIS, that houses multiple applications. It summarizes the findings from the LCA analysis performed by SUPSI based on the pilot data; it provides critical raw materials data that lets the pilots assess the material criticality of their products and components for future risk assessment; and it provides a repairability simulation based on the norm EN 45554. Since it is based on the data from the pilots, the design and implementation of the digital twin follows the needs of the pilots. The CIRC-UITS project has multiple different pilots, hence not all functionalities are relevant for all pilots. The digital twin as part of the toolbox focuses on the design phase of the product lifecycle that is mostly relevant for the producer.

In addition to the digital twin, OFFIS develops Advisory tools, such as an AI for matrix completion of LCA data (see Table 3). It is based on LCA data from PCBs used in professional data centres that is similar to the data of the pilots in CIRC-UITS. It shows that using AI on a specialized use case to help filling gaps in the LCA data. Furthermore, OFFIS is developing an AI for the BOSCH use case that supports the repairability actions for products. Since products in the automotive industry are subject to strict safety requirements, first products that might not be repairable or do not meet criteria are sorted out. The AI helps detect multiple criteria that render repair impossible. Due to the reflective surface of some parts of the electronic control unit, extensive pre-processing is necessary before using a computer vision algorithm.

Continuing the toolbox rundown, TXT is developing the Advanced HMIs module to support pilot 4 (ERION), that allows the interaction between recycling operators in EoL recycling facilities and the CIRC-UITS digital toolbox functionalities in mobility, where “traditional” Graphical User Interfaces (GUI) are not flexible enough. This module supports appliance disassembly and PCB categorization by implementing complex visualizations that leverage mobile-specific interfaces and augmented/virtual reality procedures.

Another core module of the toolbox is the CIRC-UITS Marketplace, also developed by TXT to support the ERION use case. It stands as the dedicated secure tool where EoL recycling plants and BoL manufacturers can come in contact and sell/purchase objects and components to facilitate the reuse and circularity of semiconductors and strategic materials. The Marketplace tool leverages innovative technologies such as agent-based contract negotiation strategies and blockchain-based smart contract agreements to support and improve asset selling/purchasing, ensuring transparency of the transactions and compliance with strict EU auditing regulations.

Completing the Digital Toolbox offering, the LCS&CA Tool and Advisory Services will be extensively described in the upcoming chapters for the BOSCH, CONTI and TNO pilots. While being a core part of the digital tools outlined in this chapter, such modules have been further expanded in Chapter 7.3 and Chapter 7.4.

As a last note, special mention needs to be made to data sharing within the toolbox, which is addressed by the Data Layer. It aims at addressing data sharing concerns constantly raised by companies and other important stakeholders along the value chain and, as a result, it supports all four pilot use cases and activities. Indeed, such actors are often reluctant to share their process/production data. While, on one hand, this protects their security on the other hand, this hinders the improvement of the circularity of the overall industry: the actors involved need specific information about components and materials to carry out their own sustainability and circularity assessments, thus improving their performances. In this regard, CIRC-UITS has included in its Circularity toolbox a system for secure data sharing among the value chain actors, which revolves around the Data Space technology. The Data Space is a novel technology that allows secure data exchange, ensuring that the data owner retains its ownership over their data and can set up a set of policies to handle access rights and data management. Finally, the Data Layer offers a unified, secure, trusted and traceable data storage solution to ingest outside data (shop floor data sources, local data buses, and companies' legacy systems) into the circuits toolbox to favour the flow of information within the rest of the toolbox.

7.2 Recycling process simulation modelling for assessment and advisory

The recycling process simulation models as defined and developed by MARAS within WP3 and described in D3.1 in detail as part of the LCS&CA assessment and advisory methodologies provides a rigorous and physics-based Digital Twin for the recycling processing system (see also Van Schaik and Reuter, 2024 [4] and Reuter and Van Schaik, 2023 [5]). The systemic view and the detailed mass and energy balances that these process simulation models provide, enable rigorous resource efficiency and sustainability evaluations for production

[4] Schaik, A. van and Reuter, M.A. (2024). Simulation-Based Design for Recycling of Car Electronic Modules as a Function of Disassembly Strategies. Sustainability 2024, 16(20), 9048; https://doi.org/10.3390/su16209048.

[5] Reuter, M.A. and Schaik, A. van (2023). Chapter 5: Material and product-centric recycling: design for recycling rules and digital methods. In Handbook of Recycling, State-of-the-art for Practitioners, Analysts, and Scientists. 2nd Edition - October 17, 2023.Editors: Christina Meskers, Ernst Worrell, Markus A. Reuter. ISBN: 9780323855143

and recycling processes and the systems they are a part of. The results obtained through simulation-based approach include environmental indicators, exergy, recycling and recovery rates, as well as the qualities and quantities of the recyclates, losses and emissions of materials during production recycling. The complete mass and energy balance simulation provides the mineralogical detail of all streams (both mineral and recyclate as well as off-gas and dust) to define and improve environmental assessment (in this project applied for the EoL phase of the designs which will be assessed), while at the same time providing product and recycling processing route specific EoL LCA input to LCA databases and to the LCA as performed in this project for the other life cycle stages. Resource consumption indicators that account for the quantities of materials and energy needed for a process to achieve its intended goal are obtained directly from the models as the quantities calculated in the simulated mass and energy balances. Those that account for the generation of entropy in terms of, for example, the exergy dissipation in a process or system, or the exergy cost of a product or residue can be obtained directly from process simulation tools such as HSC Sim in which the simulation models are developed (see D3.1 for a more detailed description).

This tool is applied within the four different pilots to assess in detail the recycling and circular performance at EoL for the different products and innovations. The following recycling KPIs will be calculated from the recycling process simulation models (see Table 4):

- Total recycling rate, which can be visualized by the Recycling index of the part, product or parts coming free during repair for recycling as a whole (%).
- Individual material recycling rate of all materials/elements/compounds included in the part, product or parts coming free during repair (e.g., Fe, Cu, Au, Ag, CRM recycling rate, etc.) in % which can be visualized by the Material Recycling Flower.
- Quality/purity of recovered materials (MQI – material quality indicator)
- Energy recovery in MWh/t of feed or per part/product.
- Exergy circularity indicator (ECI) [MJ].

Table 4 Indicators/KPIs calculated and derived from the recycling process simulation models as described here.

Indicators/KPIs calculated and derived from simulation models	Description/detail
Recycling Index (RI) (see Figure 41)	Total recycling rate of a product or part based on all materials/compounds present (mass or %) (based on full mass balances, hence can also be used to provide an indicator/value for 'waste'/losses/emissions from recycling).
Material Recycling Index (Material-RI) (see Figure 41)	Individual material recycling rate for all materials/elements present in a product/part (mass or %) (based on full mass balances, hence can also be used to provide an indicator/value for 'waste'/losses/emissions from recycling).
Recovered material quality Indicator	Quality/purity of recovered materials – CE level of application of recycling products.
Energy/exergy Indicators (CE Indicator)	Energy usage and recovery in recycling and exergy quantifying the CE performance of the recycling system on a physics (2nd law of thermodynamics) basis.

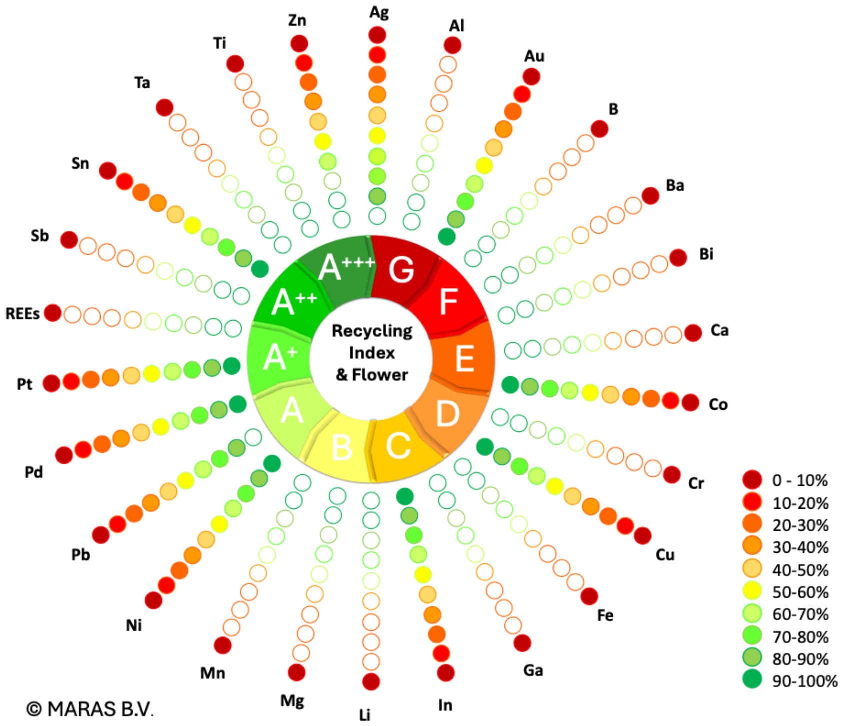


Figure 41: Recycling Index and Material Recycling Flower visualising the total and material recycling rate (Van Schaik and Reuter, 2024).

These KPIs and underlying data provide detailed and product and recycling route specific input to existing Circularity Indicators (such as Material Circularity Indicator (MCI), PCI, etc) on recycled material/recovered EoL materials, waste from recycling, energy required for recycling, etc and provides additional values to improve MCI and PCI, to name a few, to provide these indicators with a rigorous basis on these parameters.

The exergy circularity indicators as developed by MARAS as described in detail in D3.1 provide a novel and much more rigorous approach for the calculation and optimisation of CE, based on exergy and the 2^{nd} law of thermodynamics. This approach and exchange of exergy indicators will be part of the interaction with the pilots.

Repair assessment by application of (results) of digital LCS&CA tools

In section 4.4.4 a preliminary list of repair KPIs was shown, as drafted by MARAS for the repair assessment. These indicators link up with the rigorous indicators for resources, energy and exergy as provided by the Digital LCS&CA tools and provide the assessment of the material, energy and exergetic results and effects of repair. This approach will be explored for some of the pilots and is different from the EN repairability assessment standard, which focusses on assessing the possibility of repair. The repair assessment will focus on the results and impact of repair from a CE point of view.

Advisory from Digital recycling simulation tools

The recycling process simulation Digital Tool will not only be applied for the assessment of the recycling of products and part, however the KPIs and knowledge generated through the application of this approach is applied to define advisory on a rigorous physics, technology and product design unique and distinctive basis. Maintaining the material quality in the CE through the recycling of complex waste and EoL products requires that Beginning-of-Life (BoL) and EoL actors in the automotive supply chain are linked on a rigorous physics basis. The application of the digital models provides this rigorous basis as it has the depth to assess and distinguish differences in product designs with respect to recycling performance and environmental impact as well as to distinguish the more resource efficient design from the others. The application of this simulation-based methodology allows that all processing options in the recycling system, ranging from disassembly and sorting to metallurgical and other final treatment processes, are understood and optimally linked in fundamental detail and can be related to product design considerations. Hence, simulation- based modelling provides a rigorous and technology-driven basis for recycling assessments, disassembly strategies and Design for Recycling (DfR) by pinpointing and quantifying critical issues in recycling related to design.

The following advisory is defined from the application and evaluation of the Digital Process Simulation Models:

- Recommendations on the most optimal recycling flowsheet architecture or routes (based on the best available technologies at industrial level)—this will differ per product and disassembly level
- Feedback/advisory to dismantlers and OEMs on additional disassembly and modular design
- Advisory on balancing repair with recycling
- Design for Recycling advisory – Advisory to eco-designers based on metallurgical incompatibilities (qualitative from the Metal Wheel) and quantitatively based on the findings of the recycling simulations and detailed quantitative insights into the recoveries and losses of materials/elements/compounds to perform DfR.

Link to LCA/environmental assessment tools

The detailed mass and energy balances can be useful data sources for other methods used to quantify environmental impacts such as Life Cycle Assessment (LCA) and contribute to the goal and scope definition phase because the system and its objectives already defined in the simulation model can be transferred to the LCA. This has been discussed in detail by and has been summarized by the authors in the Handbook of Recycling (2024) [6].

Its main contribution would be in the life cycle inventory stage. In LCA, the life cycle inventory analysis is often performed using data from commercial environmental databases. While these contain useful inventory data for many processes, the datasets do not always fully or even not correctly represent the processes being evaluated. The digital recycling tool will be applied for some of the pilots to enhance the inventory analysis stage in EoL by generating up-to-date mass and energy balances that can be transferred to the LCA with more detail on the elements and compounds present in each stream of the process. Currently, the generated information flow in HSC Sim is directly coupled to the LCA software solutions GaBi 8.0 (2022) (www.sphera.com) and openLCA 2.0 (www.openlca.org) and will be transferred to SUPSI and TNO in the pilots.

Link to CIRC-UITS toolbox/platform by development of recycling surrogate neural net functions (AI)

MARAS has a long experience in developing AI/NN based models (Bartie et al, 2021 [7]). Based on the different designs, redesigns combined with the physics based versatile recycling flowsheet simulations in the recycling digital twin, surrogate functions that twin the simulation model will be created. Neural net surrogate

[6] Meskers, Worrell, Reuter (2024): Handbook of Recycling, Elsevier, https://doi.org/10.1016/C2017-0-03207-X.

[7] Bartie, N.J., Y.L. Cobos-Becerra, M. Fröhling, R. Schlatmann, M.A. Reuter (2021): The Resources, Exergetic and Environmental Footprint of the Silicon Photovoltaic Circular Economy: Assessment and Opportunities, Resource Conservation Recycling 169, 105516.

functions (AI) will be trained to translate the complex recycling simulation tools into easier to link and rapid calculating digital AI based tools as depicted in Figure 42 which would allow for linking these to the CIRC-UITS toolbox.

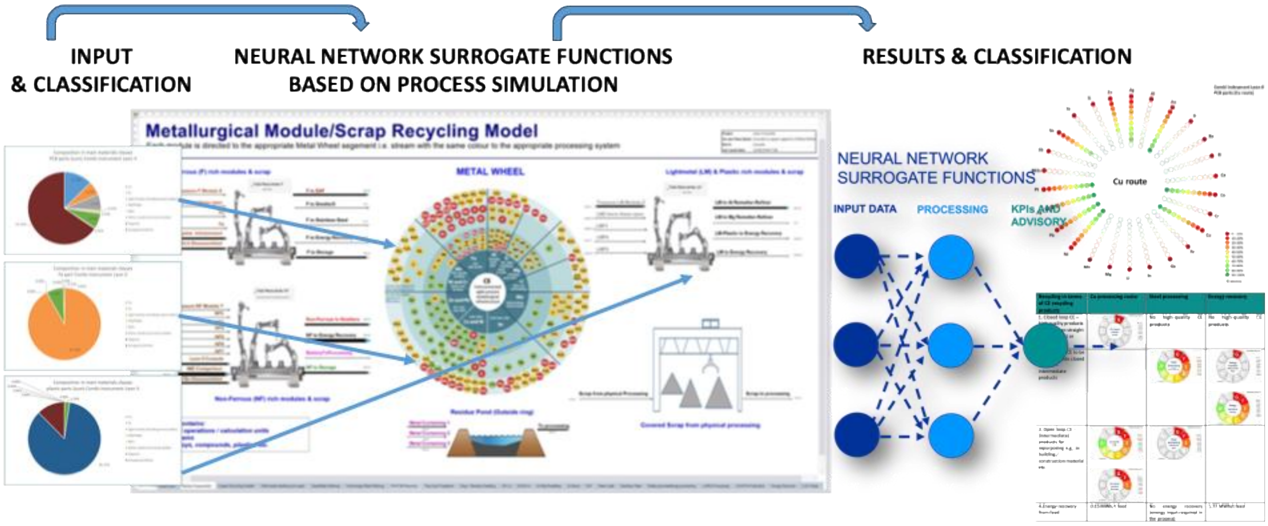


Figure 42: Creation of Neural Net Surrogate functions based on process simulations (MARAS)

7.2.1 Application of Recycling Simulation Tool for assessment and advisory of pilots: Pilot #1

To assess the recyclability of the current ECU design of Bosch in pilot #1 and to provide feedback and advisory to the current design to improve recycling performance, MARAS has applied the developed recycling simulation model to this pilot #1.

7.2.1.1 Data processing of Bosch ECU data

Successful accomplishment of recycling assessment on a rigorous simulation basis requires that detailed product data of the product/ parts for which the recycling assessment is being performed, is available. This implies in other words, that the complete "mineralogy" of the product must be available as is usual when simulating and optimizing metallurgical processes and flowsheets (see Reuter and Van Schaik, 2013 [8]; Van Schaik and Reuter, 2014 a [9] , Ballester et al, 2017 [10]). Hence the first stage in the performance of the

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[8] Schaik, A. van and Reuter, M.A. (2013). Product Centric Simulation Based Design for Recycling (DfR), 10 Fundamental Rules & General Guidelines for Design for Recycling &Resource Efficiency. Report in commission of NVMP, The Netherlands.

[9] Schaik, A. van and M.A. Reuter (2014a), Chapter 22: Material-Centric (Aluminium and Copper) and Product-Centric (Cars, WEEE, TV, Lamps, Batteries, Catalysts) Recycling and DfR Rules. In: Handbook of Recycling (Eds. E. Worrel, M.A. Reuter), Elsevier BV, Amsterdam, 595p, (ISBN 978-0-12-396459-5), pp 307-378.

[10] Ballester, M., van Schaik, A. & Reuter, M.A. (2017). Fairphone's Report on Recyclability – Does modularity contribute to better recovery of materials? – https://www.fairphone.com/en/2017/02/27/recyclable- fairphone-2/ and https://www.fairphone.com/en/2017/08/08/examining-the-environmental-footprint-of-electronics-recycling/.

assessment is to bring the BOM data as provided by Bosch on the ECU design and composition, in line with the detail and format as required for the thermodynamic process simulator HSC Sim in which the Recycling Simulation model was developed.

The following activities have been performed to process the Bosch data into thermodynamic recognisable compounds for simulation and to link the data to the recycling process simulation models:

- Processing of material descriptions/CAS no into definition of stoichiometric formulas for all materials in Bosch design;
- Data description and chemical formulas of organics have been added to the data file in terms of composition;
- Full compositional analyses are available as input to recycling simulations;
- Building up of a database containing CAS number and chemical/molecular formulas;
- Integration of data into simulation models, as is shown in Figure 43;
- Material/compound definitions in model are expanded in model to include full design of ECU.

INPUT SPECIES (1) Formula - Data from module	Temper. °C	Pressure bar	Amount kmol	Amount kg mass from data of module	Amount Nm³	Heat Content MJ	Total H MJ	Heat Cont MJ / kmol	Tot H MJ / kmol	MW kg/kmol	Dens kg/l	DBNo	T*S MJ	G MJ	Ex Phys MJ	Ex Chem MJ
*2CoO*TiO2	25,000		0,232	53,301983	0,000	0,00	-339,95	0,000	-1465,200	229,731	###########	2	9,809	-349,764	0,000	42,637
*3MgO*4SiO2*H2O	25,000		0,000	0	0,000	0,00	0,00	0,000	-5896,920	379,266	2,710	2	0,000	0,000	0,000	0,000
Ag	25,000		3,305	356,4605129	0,034	0,00	0,00	0,000	0,000	107,868	10,500	2	42,048	-42,048	0,000	328,146
Al	25,000		115,417	3114,140048	1,153	0,00	0,00	0,000	0,000	26,982	2,700	2	972,991	-972,969	0,000	91837,655
Al(OH)3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1276,120	78,004	2,420	2	0,000	0,000	0,000	0,000
Al2O3	25,000		65,613	6689,935943	1,687	0,00	-109946,37	0,000	-1675,692	101,961	3,965	2	996,683	-110943,023	0,000	984,589
Al2O3*2SiO2	25,000		28,533	6338,105926	2,438	0,00	-95334,27	0,000	-3341,154	222,130	2,600	2	1160,801	-96495,055	0,000	5006,021
AlO	25,000		0,000	0	0,000	0,00	0,00	0,000	87,027	42,981	###########	2	0,000	0,000	0,000	0,000
As	25,000		0,007	0,546059512	0,000	0,00	0,00	0,000	0,000	74,922	5,750	2	0,078	-0,078	0,000	3,590
As(CH3)3	25,000		0,000	0	0,000	0,00	0,00	0,000	-17,000	120,025	###########	2	0,000	0,000	0,000	0,000
Au	25,000		0,007	1,323178249	0,000	0,00	0,00	0,000	0,000	196,967	19,300	2	0,095	-0,095	0,000	0,340
B	25,000		2,485	26,86544558	0,011	0,00	0,00	0,000	0,000	10,811	2,340	2	4,371	-4,371	0,000	1560,835
B(OH)3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1094,800	61,833	1,517	2	0,000	0,000	0,000	0,000
B2O3	25,000		40,510	2820,290481	1,106	0,00	-51593,51	0,000	-1273,610	69,620	2,550	2	651,847	-52245,346	0,000	2740,266
Ba	25,000		0,743	101,986138	0,028	0,00	0,00	0,000	0,000	137,327	3,620	2	13,839	-13,839	0,000	575,852
BaO	25,000		0,000	0	0,000	0,00	0,00	0,000	-553,752	153,326	5,720	2	0,000	0,000	0,000	0,000
BaSO4	25,000		7,587	1770,788166	0,394	0,00	-11111,93	0,000	-1464,550	233,390	4,490	2	298,822	-11410,750	0,000	296,902
BaTiO3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1600,754	233,192	###########	2	0,000	0,000	0,000	0,000
Be	25,000		0,000	0	0,000	0,00	0,00	0,000	0,000	9,012	1,850	2	0,000	0,000	0,000	0,000
Bi	25,000		0,512	106,9470396	0,011	0,00	0,00	0,000	0,000	208,980	9,800	2	8,657	-8,657	0,000	140,631
Bi2O3	25,000		0,000	0	0,000	0,00	0,00	0,000	-567,310	465,959	8,900	2	0,000	0,000	0,000	0,000
C	25,000		28,435	341,5189637	0,151	0,00	0,00	0,000	0,000	12,011	2,260	2	48,662	-48,680	0,000	11665,847
CaCO3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1206,600	100,087	2,930	2	0,000	0,000	0,000	0,000
CaMg(CO3)2	25,000		0,000	0	0,000	0,00	0,00	0,000	-2325,760	184,401	2,872	2	0,000	0,000	0,000	0,000
CaHPO4*2H2O	25,000		0,000	0	0,000	0,00	0,00	0,000	-2421,168	172,088	2,306	2	0,000	0,000	0,000	0,000
CaO	25,000		185,152	10382,82059	3,109	0,00	-117556,45	0,000	-634,920	56,077	3,340	2	2103,232	-119659,594	0,000	23655,446
CaSO3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1159,386	120,141	###########	2	0,000	0,000	0,000	0,000
CaZrO3	25,000		0,000	0	0,000	0,00	0,00	0,000	-1765,230	179,300	4,780	2	0,000	0,000	0,000	0,000
Cd	25,000		0,015	1,651812446	0,000	0,00	0,00	0,000	0,000	112,414	8,690	2	0,227	-0,227	0,000	4,385
Cl(g)	25,000		0,000	0	0,000	0,00	0,00	0,000	121,302	35,453	0,002	2	0,000	0,000	0,000	0,000
Cl2(g)	25,000		0,000	0	0,000	0,00	0,00	0,000	0,000	70,906	0,003	2	0,000	0,000	0,000	0,000
Co	25,000		0,036	2,140318041	0,000	0,00	0,00	0,000	0,000	58,933	8,860	2	0,325	-0,325	0,000	11,382
Co(NO3)2*6H2O	25,000		0,000	0	0,000	0,00	0,00	0,000	-2208,566	291,035	1,870	2	0,000	0,000	0,000	0,000
Co3O4	25,000		0,000	0	0,000	0,00	0,00	0,000	-918,800	240,797	6,110	2	0,000	0,000	0,000	0,000
CoO	25,000		0,000	0	0,000	0,00	0,00	0,000	-237,944	74,933	6,450	2	0,000	0,000	0,000	0,000

Figure 43: Integration of compositional data into HSC Sim recycling simulation model

7.2.1.2 Qualitative recycling assessment

The mass-based data of the Bosch ECU and parts/modules created during different disassembly levels as defined by Bosch have been used as a preliminary basis to perform a qualitative recycling assessment (to provide fast feedback to Bosch on recycling). The composition of the total ECU and all parts created during the different levels of disassembly are shown (Figure 44). The full compositional data as shown in Annex D [11] has been classified into major material groups corresponding to the various sections in the Metal Wheel, hence corresponding to different (metallurgical and final treatment) processing infrastructures. This provides a qualitative insight into the (in)compatibility of the different parts and their composition with Best Available

[11] ANNEX D – Full compositional data BOSCH ECU.

Technique (BAT) processing infrastructures as visualized by the Metal Wheel and present in industry. At the same time, this allows for the expert-based selection of most suitable processing option(s) to be assessed within the Recycling Simulation Model by MARAS (see below section on recycling assessment for detail) (see Annex D).

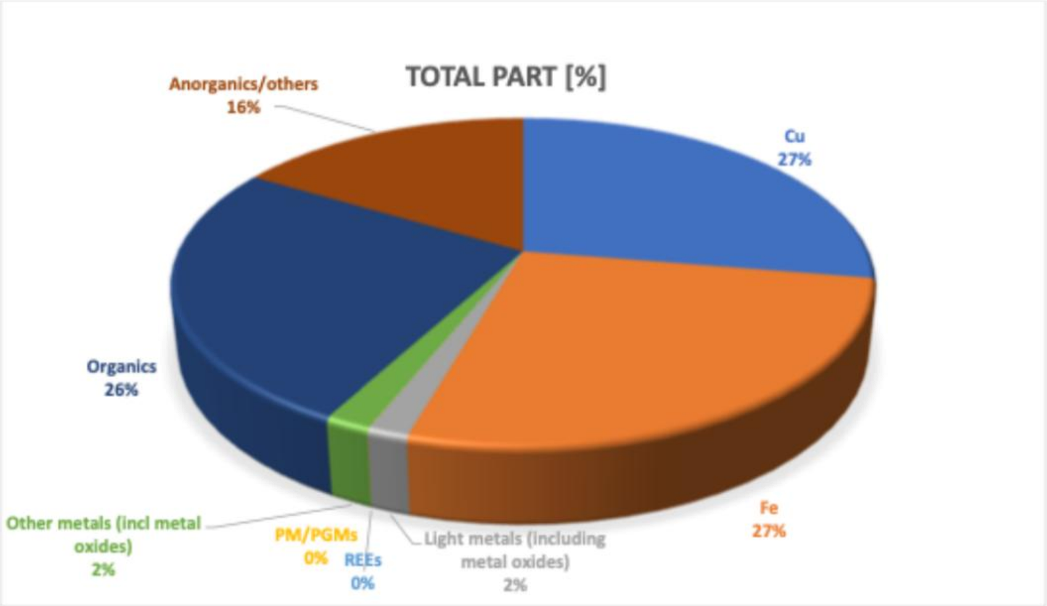


Figure 44: Mass based assessment of the Bosch ECU .

7.2.1.3 Exergy calculations on ECU design for qualitative recycling advisory and input for Bosch repair assessment

The aim of a circularity approach and circularity indicators is to identify and minimize residues and losses, i.e., to minimize the creation of entropy, across whole value chains of the CE in addition to closing material loops through EoL recycling. Exergy was discussed as a key aspect that defines the efficiency of the CE (Abadias Llamas et al., 2019 [12]). Therefore, exergy values have been included in the recycling and circularity assessment as performed for the pilot 1#.

HSC Chemistry Sim 10 calculation modules automatically utilize extensive thermochemical databases, which contains enthalpy (H), entropy (S) and heat capacity (C) data for all materials and compounds included, allowing not only recycling rate calculations, but at the same time environmental analysis including exergy assessment (not part of this deliverable). This quantifies therefore also each stream not only in kg/h units but also in MJ/h or kW. This is rather important to analyse the true losses also in terms of thermodynamics of all materials, i.e., in terms of exergetic dissipation or losses in line with the second law of thermodynamics. The simulation-based approach underlying the recycling system assessment hence provides physics- based exergy (kW) and energy (kW) calculations and values, which can be applied to assess the CE of recycling.

The exergy values as calculated directly from the recycling simulation models for the input ECU are also applicable within the Repair Assessment as defined by Bosch within Pilot 1# to assess and evaluate Repair on

[12] [12] A. Abadías Llamas, A. Valero Delgado, A. Valero Capilla, C. Torres Cuadra, M. Hultgren, M. Peltomäki, A. Roine, M. Stelter, M.A. Reuter, Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production, Minerals Engineering, Volume 131, 2019, Pages 51-65, ISSN 0892-6875, https://doi.org/10.1016/j.mineng.2018.11.007.

an extended basis compared to the EN standard. By using energy values combined with exergy (all in kW or related unit), these indicators are combined for Repair assessment (see section 2.4.1).

Figure 45 shows the exergy values as calculated from the MARAS recycling simulation models for the Bosch ECU design and modules/parts created during different levels of disassembly as defined by Bosch for the full chemical composition of the Bosch design as derived from the performed data processing as discussed above. This data has been linked to the Bosch date file and format and provided to Bosch for including these values in their Repair Assessment.

	TOTAL PART	SOLENOIDS	HOUSING	BODY	COVER	FRAME	CIRCUIT	PCB	COMP1	COMP2	COMP3
INPUT SPECIES Formula	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ	EXERGY MJ
*2CoO*TiO2	42,63692775	0	81,06679574	90,975794	0	29,50751788	194,2465769	205,6651935	0	0	0
*3MgO*4SiO2*H2O	0	0	0	0	0	0	0	0	0	0	0
Ag	328,146098	4,854902817	619,5375891	695,2652262	0	178,408606	1563,618647	1606,866529	0,21040254	4257,370492	0,024207414
Al	91837,65545	0	174613,5298	195956,9806	0	233,5887054	524785,2672	555615,0191	0	1687,958205	0
Al(OH)3	0	0	0	0	0	0	0	0	0	0	0
Al2O3	984,5885787	0	1872,026091	2100,848547	0	0	5630,413518	5961,392494	0	0	0
Al2O3*2SiO2	5006,020741	0	9518,088716	10681,50863	0	0	28627,15195	30309,97426	0	0	0
AlO	0	0	0	0	0	0	0	0	0	0	0
As	3,590271903	7,558423613	0,013664619	0,01533488	0	0	0,041098496	0,043514436	0	0	0
As(CH3)3	0	0	0	0	0	0	0	0	0	0	0
Au	0,339919712	0	0,646298955	0,725297701	0	0	1,94384597	0,18236183	15,56128353	117,8527341	10,53273754
B	1560,834924	0	2967,659554	3330,404042	0	0	8925,70384	9450,35037	0	0	1,043630725
B(OH)3	0	0	0	0	0	0	0	0	0	0	0
B2O3	2740,266049	0	5210,145285	5846,994442	0	0	15670,33311	16591,50006	0	0	0
Ba	575,8521732	0	1094,884012	1228,714437	0	0	3293,036229	3486,614508	0	0	0
BaO	0	0	0	0	0	0	0	0	0	0	0
BaSO4	296,9020425	0	564,5082444	633,5095064	0	0	1697,847517	1797,429983	0	0	5,408361583
BaTiO3	0	0	0	0	0	0	0	0	0	0	0
CH2ClO(CMRg)	97,69648692	0	185,7530917	208,4581591	0	0	558,6816997	582,6726583	0	0	213,6682757
C10H10O4(DMT)	4972215,846	955657,9866	8592452,96	7678509,375	16069543,58	12218707,88	50674,59837	53653,4607	0	0	0
C10H18O4(TESI)	0	0	0	0	0	0	0	0	0	0	0
C10H8O2(23DI)	0	0	0	0	0	0	0	0	0	0	0
C10H8O4	5897,964869	0	11213,96729	12584,67871	0	0	33727,77406	0	0	0	862103,6034
C11H30O3Si4	0	0	0	0	0	0	0	0	0	0	0
C12H10(BPH)	0	0	0	0	0	0	0	0	0	0	0
C12H11N(4AB)	1102,872194	0	2096,922073	2353,23413	0	0	6306,823628	0	490220,431	0	91018,23143
C12H12O(1ENg)	30,79808351	0	58,55726659	65,71486851	0	104,8293166	0	0	0	0	0
C12H22N2O2	6,040898032	0	11,48573016	12,88965983	0	0	34,5451437	0	0	0	882,9960972

Figure 45: Exergy values as calculated from the MARAS recycling simulation model for the Bosch ECU design and modules/parts created during different levels of disassembly as defined by Bosch

Exergy values as calculated from the MARAS recycling simulation model for the Bosch ECU design and modules/parts created during different levels of disassembly as defined by Bosch. Not only provides the mass-based assessment a basis for Design for Recycling and Recycling Advisory, the same applies for the assessment based on exergy values of the input design. Figure 46 shows the exergy-based assessment of the Bosch ECU (sub-parts according to the disassembly tree as defined by Bosch can be found in ANNEX D). From these pie-charts, it becomes clear that the organics as contained in the ECU design are predominant in the exergy content of the parts/modules. This is caused by the fact that are most ‘far away’ from the standard state (the basis for the exergy value as explained in detail by e.g. Abadias Llamas et al., 2019) and in the Handbook of Recycling (2023). This dictates that recycling from a CE perspective, should be focussed on keeping these materials in the chain.

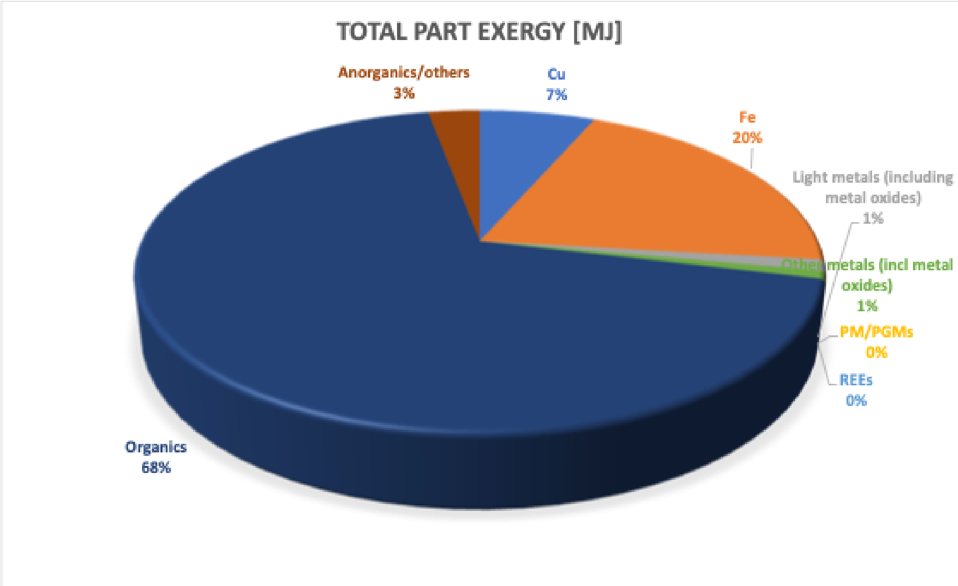


Figure 46: Exergy based assessment of the Bosch ECU (sub-parts according to the disassembly tree as defined by Bosch can be found in ANNEX D).

By including both exergy and material recovery KPIs in the evaluation of the recycling assessment as is done in the Recycling Assessment Models, a full picture of KPIs is available and will be used as the basis to define Design for recycling and Disassembly and Recycling advisory in this project. This will be discussed in the next deliverable reporting of the results of Recycling Assessment and Advisory in the follow up of the project.

7.2.2 Recycling assessment of the Bosch ECU design

The recycling of the Bosch ECU design and different disassembly levels have been assessed by the application of the recycling flowsheet simulation models as developed by MARAS.

7.2.2.1 Set up of recycling system flowsheet simulation model for recycling assessment

The recycling processing flowsheet, including all (industrial) available processing routes for the recycling of the car parts, provides the basis for the calculation of the recycling rates. This processing flowsheet in the simulation models has been developed and updated and expanded within CIRC-UITS project, investigating and including best suitable technologies for the processing of the selected car parts for disassembly and adopting and processing all materials/compounds/elements as present in the designs as considered within the CIRC-UITS project (see also D3.1 for an extensive description of the Recycling Simulation Models). This has been done based on existing background within MARAS (Reuter et al, 2018; Van Schaik and Reuter; 2016; Reuter et al; 2015; Van Schaik and Reuter, 2014).

To allow for the assessment of recycling, calculation of recycling KPIs as listed above as well as for the optimization of the industrial feasibility of the metallurgical recycling processing options, all modules and hence all materials and compounds present in the (disassembled) ECU parts are included in the recycling assessment. Including all materials, elements and compounds in recycling assessment is crucial, as material combinations are affecting the mutual recovery rates in processing.

The Metal Wheel in Figure 47 depicts the basic metallurgical infrastructure in the centre band, that makes the recovery of elements in each segment possible due to the refining and alloying infrastructure and compatible chemistry and material physics (Reuter and Van Schaik, 2013). To assess the recyclability of the ECU and disassembled parts, these parts and disassembled sub-parts are directed into the recycling flowsheet simulation model following the segments in the Metal Wheel, which is covered in the simulation models by the complete flowsheets and range of reactors composing the different (metallurgical) processing infrastructures. On this basis, the effect of the different recycling processing routes on the recyclability can be determined and the most optimal/suitable recycling processing flowsheet for the design and part under consideration can be determined. To render the simulations viable and realistic, the selection of the most suitable range of metal and plastic processing routes (from the entire range of infrastructures available to process the different car parts (or modules)) is based on the expert knowledge within MARAS. Most suitable routes imply the recycling processing infrastructure in which the compounds of the module are most optimally recycled with a minimum of losses and emissions. This will differ per module, due to its specific material composition as defined in the design. For some modules, different options in processing might be considered, depending on which of the materials is preferred to recycle from the car part's material content.

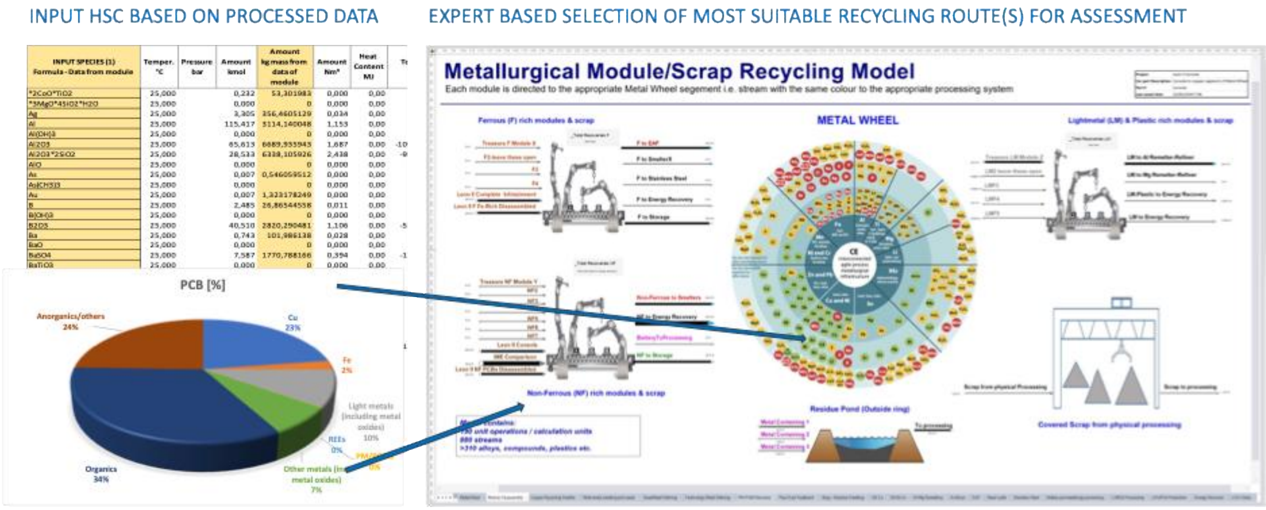


Figure 47: The basic metallurgical infrastructure and simulation models; Reuter and Van Schaik, 2013.

The flowsheets included in the Recycling Simulation Model and filling in the detail behind the Metal Wheel cover the complete metallurgical (and other final treatment) recycling processing infrastructures present in industry for the processing and recovery of all materials and compounds of ECU design. Figure 48 shows some examples of the different infrastructure flowsheets as included in the model.

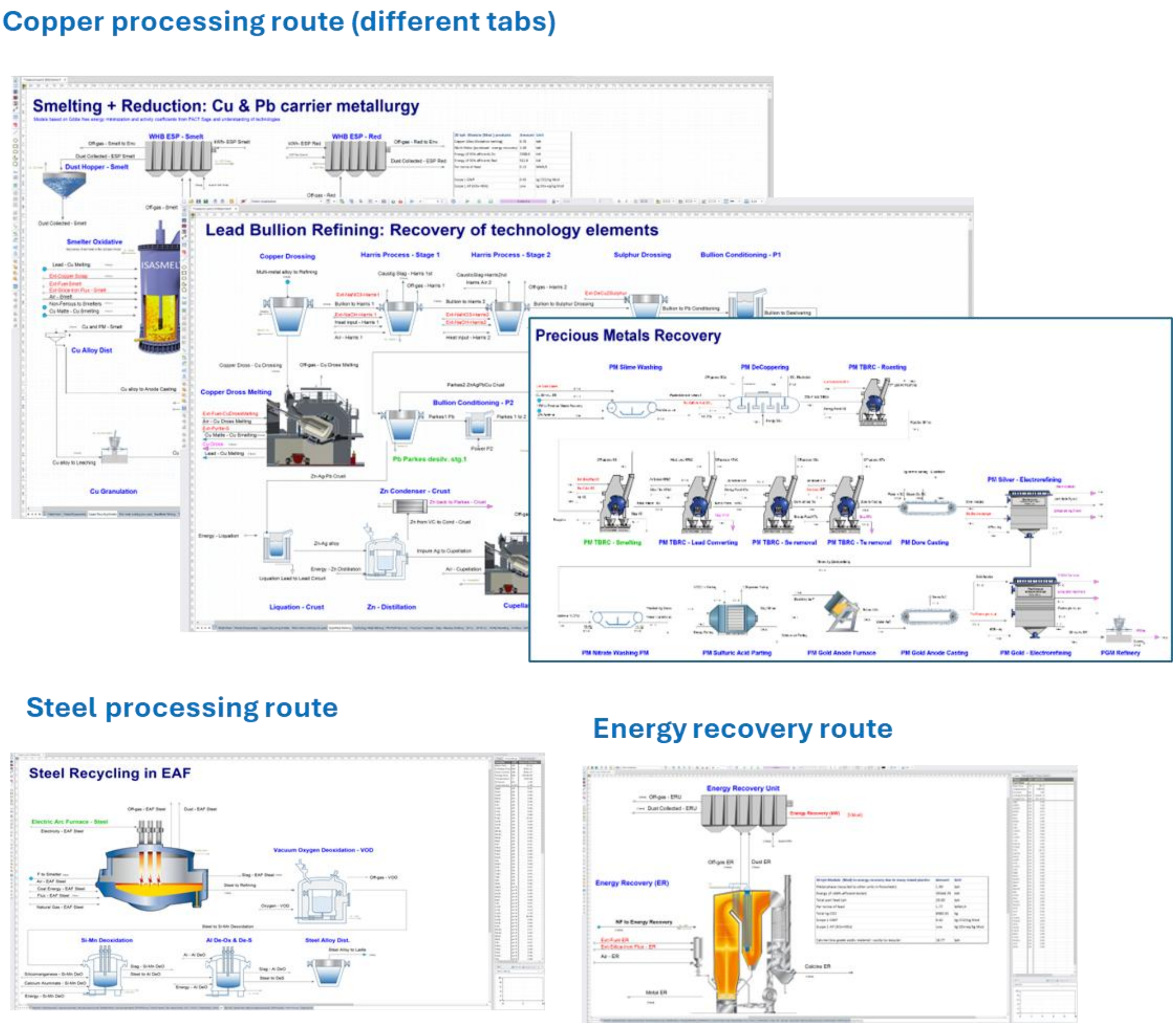


Figure 48: Example of different Recycling Processing Routes (and range of tabs/flowsheets) included in the recycling simulation model.

7.2.2.2 Results from Recycling Simulation Assessment

The recycling simulation model has been applied to assess the design and effect of individual parts and disassembly on the recyclability of the ECU. The best suitable recycling route(s) for recycling of the ECU and parts is assessed as described above. For the ECU and parts, currently the Cu processing route (see tabs in Figure 48) has been assessed based on the composition of the ECU and parts.

The HSC Sim simulation model as applied currently has:

- Around 200 reactors/unit operations;
- 840 streams;
- over 300 alloys, compounds, organics, etc being processed.

The 300 alloys, organic and inorganic compounds, elements, etc. cover both the compounds/elements/materials from the ECU as input to the recycling processes as well as the compounds, alloys, etc being the phases created during the processing of the ECU and parts, either as intermediate and/or end products. It is a globally unique model to assess recyclability and at the same time analyse design changes and improvements in complete detail.

Figure 49 presents the results for the total recycling rate defined for the 3 levels of CE (see Van Schaik and Reuter, 2024) for the ECU and a selection of composing parts (all results are available). It is important to understand in the context of this project that the recycling of a product within the circular economy implies creating the same material quality after recycling so that it can be applied in the same product. This definition is considered in the definition of the recycling results. Therefor the three levels of CE have been defined in order to present the results of recycling;

1. **Closed loop CE** – recycling into high quality products with material properties equal to original product/material.
2. **Open loop CE to be processed into closed loop CE** – recycling into intermediate products, such as low-grade alloys, calcine, etc which require further physical sorting and/or chemical upgrading to achieve the required high quality material properties/alloy quality to render closed loop CE. At the same time, open loop CE products suitable for repurposing could also be produced as product from sorting/upgrading of the intermediate products to render closed loop CE. The possibilities of processing of open loop intermediate into closed loop CE products is subject to economic, thermodynamic and environmental constraints.
3. **Open loop CE** – recycling into (intermediate) products such as slag and flue dust for repurposing e.g. as building/construction material etc. - requires significant energy and thus exergy dissipation and thence costs to convert to level 1 closed loop CE materials

The three different levels of closed and open loop CE in recycling, correspond to the three outer circles in the Metal Wheel (with closed loop CE in the most inner circle (after the dark blue base metal circle) to the Open loop CE as reflected by the most outer circle. It reveals the difference in total recyclability per CE level for the total ECU and different parts.

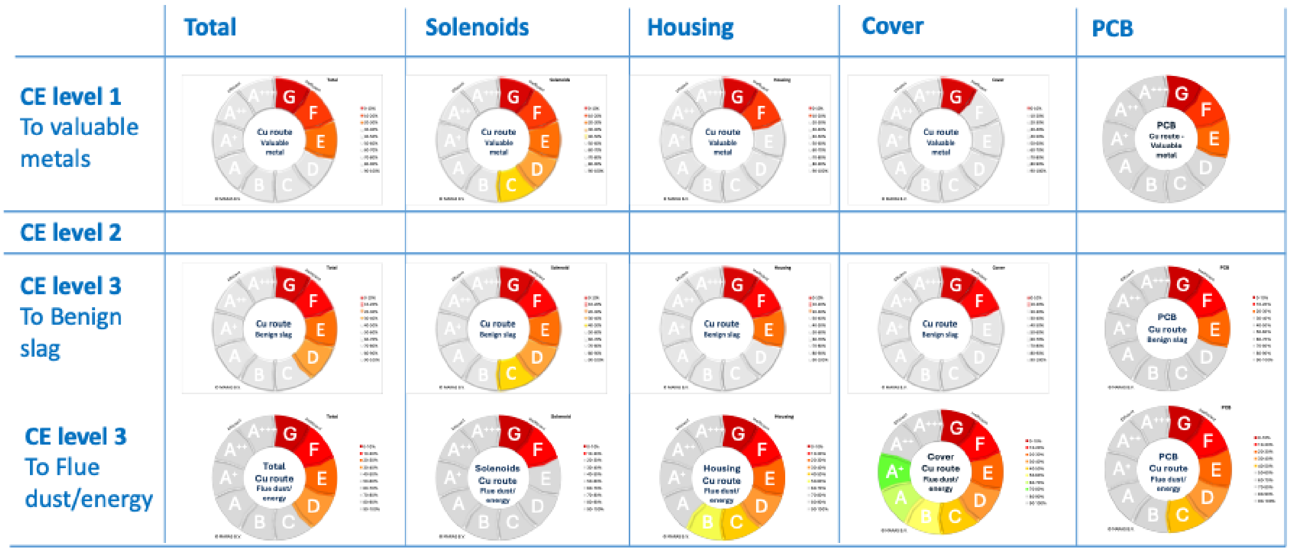


Figure 49: Total recycling rate of the total ECU and for some selected parts (all available from model) presented for the 3 levels of CE.

The Material Recycling Flower (Figure 50) combined with the RI of Figure 49 depicts the combination of individual elemental recycling rates of a selection of materials / elements / compounds that are recycled into high quality products. Developed by Van Schaik and Reuter (Van Schaik and Reuter, 2016), this visualises the individual material recycling rates and illustrate the differences in recycling behaviour and performance of different elements / materials also relative to the total recycling rate. Whereas the overall recycling rates provide information on the recyclability of the entire part or product, the individual recycling rates/KPIs are the basis for true CE assessment. Recycling of complex products is a trade-off between bulk and minor element recycling, where often the one material will (to a more or lesser extent) be ‘sacrificed’ for the recovery of the other. This is not always reflected by the overall recycling rates due to the lower weight of precious (scarce, critical) elements present). Therefore, the Material Flowers as developed by MARAS serve very well as a tool in this discussion and help to make the choice for a certain recycling route, not only driven by weight-based considerations, but addressing the recycling of materials and elements, which are of interest to recycle or defined as critical and therefore require focus in selecting the most optimal recycling options.

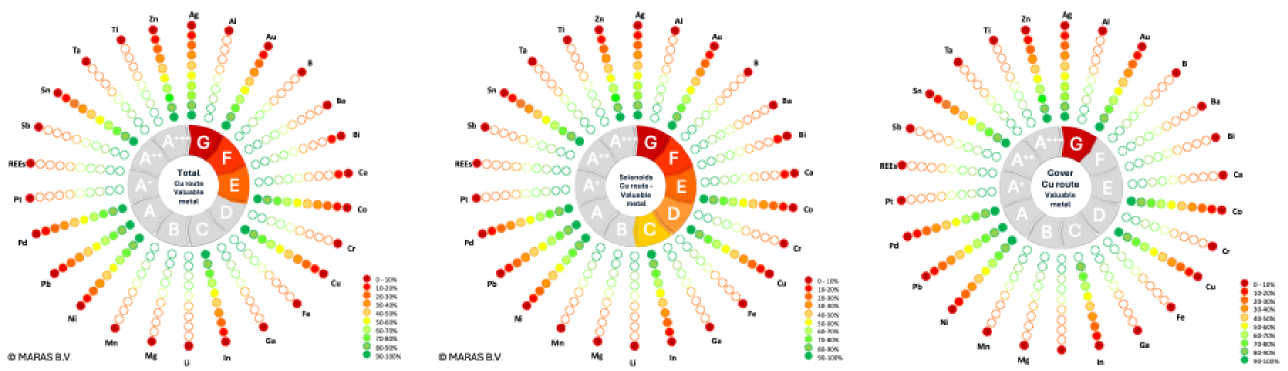


Figure 50: A selection of results (all results are available from the model) from the recycling simulation-based assessment of the Bosch ECU and the respective disassembly levels presented for both Total Recycling Index and Individual Material Recycling Rates.

In the current deliverable, only the recycling KPIs related to recycling rates are presented. Although already included in the assessment, the results and findings on the other KPIs such as energy and exergy will be reported on in the follow up deliverable. In the follow up of this work, the recycling assessment and results will also be further evaluated and DfR and Recycling and Disassembly advisory will be provided to Bosch on this basis, also combining the Recycling rate KPIs with energy and exergy considerations for recycling, in which exergy of recyclates will be part of. Furthermore, this work will be expanded to assess the upcoming improved/new designs of the ECU and compare the different designs from an EoL perspective.

7.3 LCS&CA Tool

The LCS&CA Tool in the CIRC-UITS project comprises two main components: GRETA, a pre-existing tool developed by SUPSI in previous initiatives and enhanced in functionality within this project, and the Recycling Simulation developed by Maras. Together, these components provide a comprehensive solution for assessing the sustainability and circularity of products and processes in manufacturing.

GRETA is a web-based application developed with a microservices architecture, tailored to assess the sustainability and circularity of products and processes in the manufacturing sector. It offers diagnostic and advisory functionalities, enabling users to optimize production practices through data-driven insights. Designed with manufacturing companies in mind, especially those focused on sustainable, early-stage product design, GRETA allows users to simulate and compare various production scenarios even when data availability is limited. This capability supports the generation of comprehensive sustainability profiles, balancing environmental, economic, social, and circular factors to guide users toward eco-friendly and cost-effective production decisions.

Within the CIRC-UITS project, GRETA's functionalities were expanded and adapted to address specific needs and use cases of the project's pilots. The enhancements included:

- Integration with CIRC-UITS platforms and tools: GRETA's architecture was augmented with an integration layer to enable seamless interaction with external components. These components functioned as both data sources and recipients of GRETA's outputs, ensuring effective communication and data flow across systems.
- Advanced model editing and data management: A model editor was added for formalizing process and product models from a sustainability perspective, allowing users to directly import these models into GRETA.
- Integration with external data sources such as dataspaces, blockchain solutions, and databases, enabling GRETA to collect inventory data or disseminate sustainability indicators.
- Connections to real-time sources like sensors, IoT devices, and middleware, which provided dynamic data for specific assessments.
- Linking to external tools, such as ERP systems or CAD applications, which could leverage GRETA's assessments to enhance their capabilities.

GRETA's assessment results were integrated into the digital twin and other external tools through a Data Manager sub-module within the Data Layer developed by TXT. This layer ensured the accessibility and interoperability of key data across platforms, enabling real-time updates and synchronization. The result was a robust connectivity framework that supported digital twin precision and utility, empowering users to make informed, sustainable decisions. The combination of GRETA's advanced simulation capabilities and its integration into broader ecosystems has positioned it as a critical tool for driving sustainability and circularity in the manufacturing sector.

7.4 AI-based distributed Advisory services

The AI-based Advisory Distributed Services in the project operate as an interconnected network of embedded functionalities distributed across multiple platform's components. These services are not standalone tools but are integrated into key project elements such as GRETA, the MARAS Simulation, and the Digital Twin, collectively providing decision-makers with guidance during the Eco-Design, Energy analysis, Disassembly process, End-of-Life stages of a product lifecycle, and LCA experts conducting LCA. The advisory functionalities are here described:

- Design Tool: An interface within the Digital Twin, the Design Tool enables designers to specify product requirements and receive instant feedback on key performance indicators (KPIs). Leveraging historical assessment results, this AI-driven feature provides rapid insights without the need for a full assessment, offering valuable support during the early design phase.
- Decision Tool: The Decision Tool is another feature of Digital Twin, designed to assist in finalizing design choices. Unlike the Design Tool, it provides a comprehensive view of all KPIs, including

repairability metrics, after completing the full assessment process. This tool supports well-informed decision-making by offering a detailed comparison of options based on fully assessed data.

- CRM Dashboard: This interactive dashboard supports designers in selecting raw materials by presenting a criticality analysis. It uses visual aids such as pie charts, maps, and radar charts to display detailed information on material availability, import dependency, economic risks, and supply risks. This decision-support tool ensures that designers can identify critical raw materials and evaluate their impact on sustainability and supply chain resilience.
- LCI Matrix Completion: This advanced functionality supports Life Cycle Assessment (LCA) experts by addressing incomplete life cycle inventory (LCI) datasets. Using artificial intelligence techniques like Monte Carlo simulation, the tool analyzes similar scenarios to generate consistent and plausible data, filling gaps in the LCI. This ensures more accurate and reliable LCA results, even when critical data is missing.
- Repairability Assessment Tool: Based on the EN 45554 standard, this tool evaluates the repairability of energy-related products. By inputting specific parameters organized into weighted categories, designers can calculate a product's repairability score. Scores are assigned to individual components, which are then aggregated to provide an overall repairability assessment, supporting design improvements for repair and reuse.
- Recycling KPIs and Recycling Routes: These functionalities rely on results from the Recycling Simulation to advise on optimal recycling strategies. Detailed process simulation models link input and output flows within the recycling system, enabling designers to identify recycling hotspots and improve designs for recycling performance.
- Metal Wheel: A qualitative advisory feature that aids in design for recycling (DfR). By analyzing process-specific recycling models, the Metal Wheel identifies critical areas for design improvements. Combined with quantified recycling KPIs, it provides actionable insights for achieving high recycling efficiency tailored to specific design parameters.
- GRETA Comparison: This feature allows designers to compare the sustainability impacts of alternative designs for the same product. Using radar charts, it visualizes real-time LCA results calculated for each design option. This comparative analysis supports data-driven decision-making, guiding designers toward the most sustainable and efficient solutions.
- GRETA Hotspot Identification: This advisory identifies the most impactful phases and parameters within a product or process lifecycle. It uses a tailored computational algorithm and REST API integration to analyse user-defined criteria like LCA indicators and impact thresholds, visually marking critical phases and parameters with a "fire icon" in the GRETA UI.
- GRETA Best Customization: This advisory optimizes product or process parameter configurations based on user-defined preferences such as sustainability and profit weights. Users specify variable ranges, constraints, and options via the GRETA UI, and the advisory evaluates combinations to recommend the best customization.
- GRETA Chatbot: The GRETA AI-based chatbot is designed to support designers and manufacturers in interpreting sustainability results and optimizing industrial processes and products. Integrated into the GRETA platform, the chatbot provides real-time interactive assistance, helping users understand sustainability assessments, such as LCA, LCC, SLCA, and CE. It offers targeted recommendations for improving processes and product configurations to reduce environmental impact and answers specific questions related to customization, including energy mix or production materials. Leveraging advanced AI algorithms and data from GRETA, the chatbot efficiently guides users in enhancing sustainability performance, making it an essential tool for eco-design and circular economy practices.

These advisory services leverage advanced simulation, analytics, and visualization techniques to provide data-driven insights at various stages of product design and lifecycle management. By integrating these advisory functionalities into tools like GRETA, MARAS Simulation, and Digital Twin, the platform empowers users to make informed, sustainability-oriented decisions that align with the project's goals for eco-design and circularity.

8 Annexes

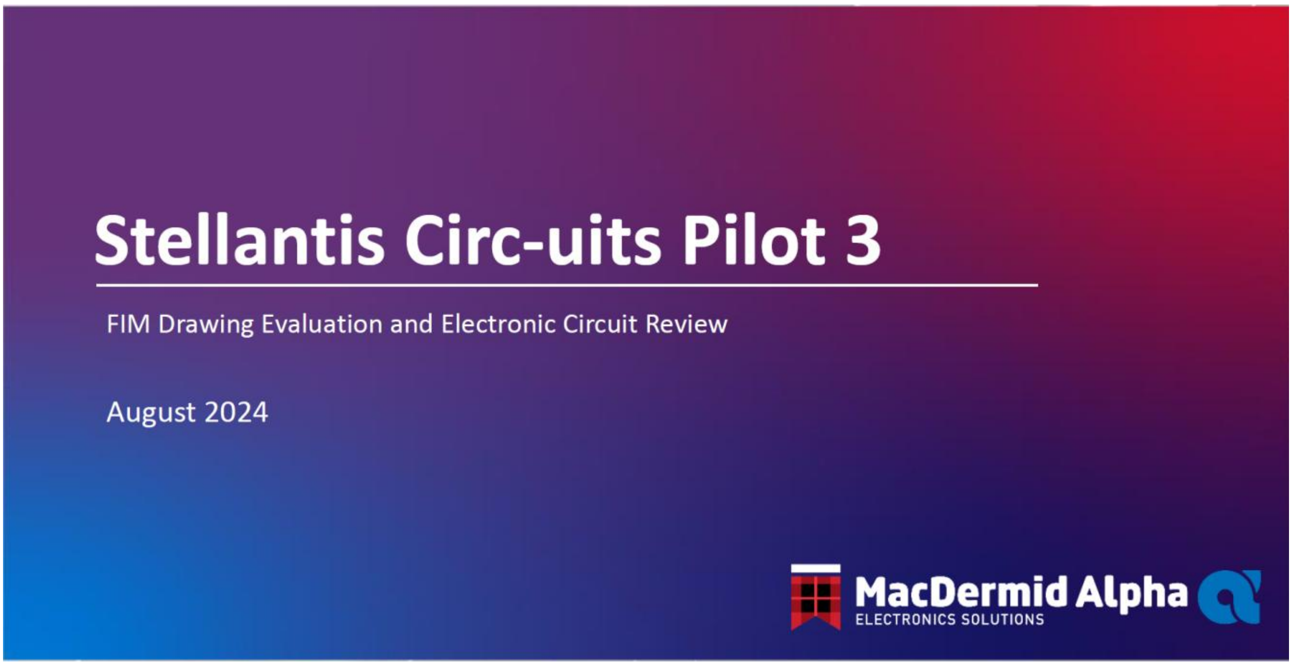
ANNEX A – Alpha design review report of TNO pilot 3 demonstrator

ANNEX B – Pilot 4 PCBs categories – CRMs (pdf file)

ANNEX C – PCB categories identification strategy and tips (excel file)

ANNEX D – Full compositional data BOSCH

8.1 Annex A



Content

1	**Stellantis CIRCUITS Project - FIM Evaluation** ▸ Stellantis Circuits Pilot 3 – Overview & Summary ▸ FIM Rules and Part Overview ▸ Specifications Requirements ▸ Comments on Drawing ▸ FIM Rule 1 to Rule 12 Feedback
2	**Stellantis CIRCUITS Project – Electronic Circuit Design Evaluation** ▸ Stellantis Circuits Demonstrator V2 Overview ▸ Circuits Demonstrator V2 – Graphic Layers ▸ Circuits Demonstrator V2 – Printed Silver Inks & Requirements ▸ Circuits Demonstrator V2 – Formability Inputs ▸ Summary

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1. Stellantis Circ-uits Pilot 3

Drawing Evaluation & FIM Rules

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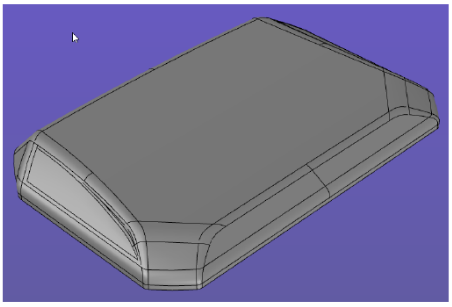
Overview: Stellantis Circ-uits Pilot 3

OEM	Stellantis
Tier 1	-
Processor	TNO
Drawing Supplied By	Pim Ostendorf/TNO
File Name	Mould_IME2_v4 v2.step
Drawing / Revision Number	v1
Electronic Functionality	Yes
Specific Requirements	500µm Uncoated Polycarbonate



Summary: KEY POINTS FOR THE PART

- Changes are recommended for the part to be feasible.
- Key Points:
  - FIM Rule 3: Negative drafts found near some of the edges, may induce issues in forming.
  - The thickness of the part is between 3 to 9 mm. If no molding is intended, then this thickness is much higher than what we expect.
  - Pack density rule should be followed for the forming tool design. It is critical to allow enough film around formed areas to stretch. If there is not enough film to stretch, the film will crack in the formed area.
  - MAES can review tool design to ensure pack density rules are adhered too prior to tool design approval before manufacture.

Stellantis Circ-uits Pilot 3

FIM Rules, Specifications and Feedback

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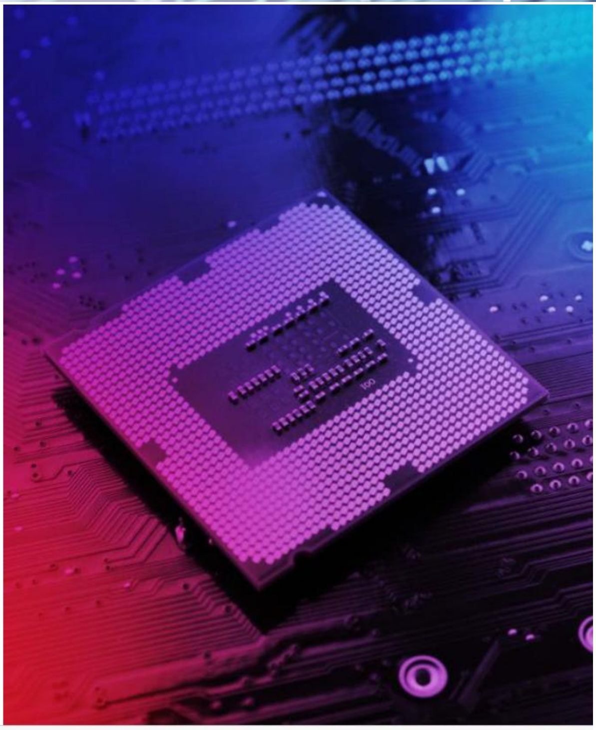

FIM RULES & PART OVERVIEW

FIM Rule 1 -	Maximum forming areas suggested are: 400mm x 245mm, 720mm x 390mm or 1400mm x 400mm.	7
FIM Rule 2 -	Minimum radii 2x film thickness.	8
FIM Rule 3 -	Minimum recommended 2° draft angle, no negative draft angle.	10
FIM Rule 4 -	No unsupported lenses.	12
FIM Rule 5 -	Maximum draw within film gauge acceptable limits - see data sheet.	14
FIM Rule 6 -	Pack density rule followed for forming tooling.	16
FIM Rule 7 -	No first surface forming contact with XtraForm.	17
FIM Rule 8 -	Changes in mold thickness should be avoided especially close to graphics.	19
FIM Rule 9 -	Parting line needs to be situated to allow the positioning of the film in the tool.	23
FIM Rule 10 -	Registration requirements considered and achievable – supplier specific.	25
FIM Rule 11 -	Holes and/or depressions within a part need to be 25 % or less in depth or height than their narrowest width, must also meet FIM Rule 2, 3 & 6.	27
FIM Rule 12 -	The length of film between the feature bars and/or rails within a part need to be at least 4 times the height of the feature bar and/or rail, must also meet FIM Rules 2, 3, & 6.	29

Acceptable	More info needed or possible areas of concern	Changes recommended

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Semiconductor & Assembly Solutions
Film & Smart Surface Solutions 7

SPECIFICATION REQUIREMENTS

Specifications

- When properly cured, XtraForm will pass, and has been validated to many automotive interior specifications such as Toyota TSM5749G, Stellantis MS-PZ-5-1, Ford WSSM15P34-E, and GM GMW16717.
- XtraForm films are used in projects requiring Stellantis MS 90053.
- XtraForm is fulfilling the Volkswagen specification TL 226, only the gloss is changing slightly after Hydrolysis Aging which is accepted for all current applications in the Volkswagen Group.
- XtraForm passes all the major OEM chemical resistance tests for sun cream including TL226 and 40 % concentrations of DEET.
- When properly cured, XtraForm will pass, and has been validated to Stellantis MS-PZ-5-1, Coating Systems For Purchased Painted Interior Parts.
- The use of Film Insert Molding will protect the part from abrasions and deep gouges. This feature is because the decorated surface is protected beneath a hard coated film of 180μm, 250μm, or 380μm, and 250μm in the case of XtraForm Antiglare.

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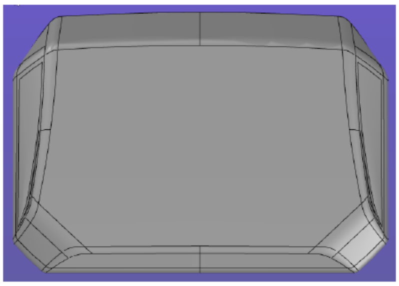
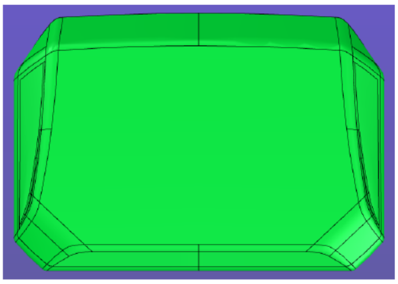
COMMENTS ON DRAWING PROVIDED

Report based on below assumptions.

- Film covers full surface.
  - The film and resin layer are not separated in the CAD file.
- Graphics can be printed on the back surface of the film as well as adding conductive functionality.
- Part consists of the following:



XF Film



1st Shot Mold

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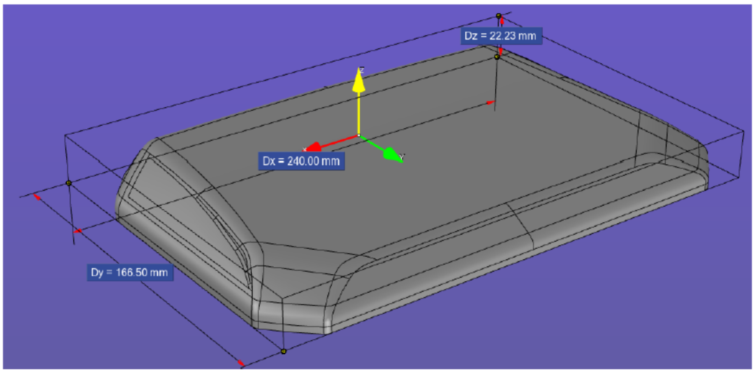
FIM RULE 1

Maximum forming area to be determined.

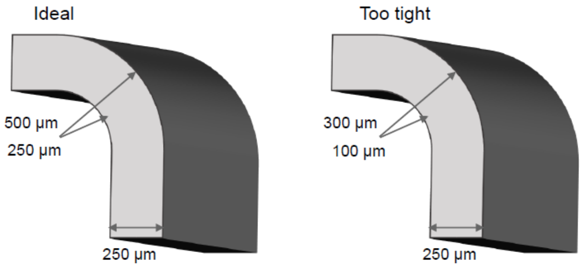
- The size of this part is approximately 240 mm long x 166.5 mm wide.
- The size of this part is not seen as a problem for FIM.
- Parts of this size would typically be made using XtraForm in a 250 µm thickness.



FIM RULE 2

No radii less than 2 times film thickness.

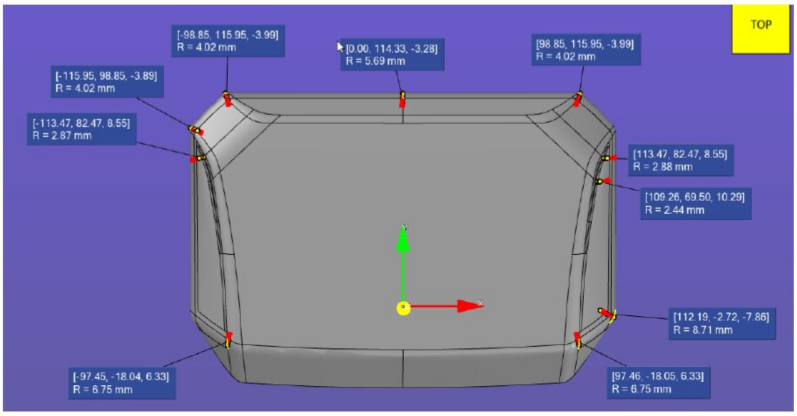
- Internal corners of buttonholes should be at least 3 times the film thickness.
- A part designed with a larger minimum radius will allow for full compatibility with all three gauges of XtraForm film.
- When choosing an XtraForm high gloss gauge consider the following:
  - XFG180: Minimum radius = 360 µm / 0.36 mm
  - XFG250: Minimum radius = 500 µm / 0.50 mm
  - XFG380: Minimum radius = 760 µm / 0.76 mm



FIM RULE 2

No radii less than 2 times film thickness.

- Minimum measured radii is 2.44 mm. Since the intended sheet thickness to be used is 0.5mm, it conforms to the rules.



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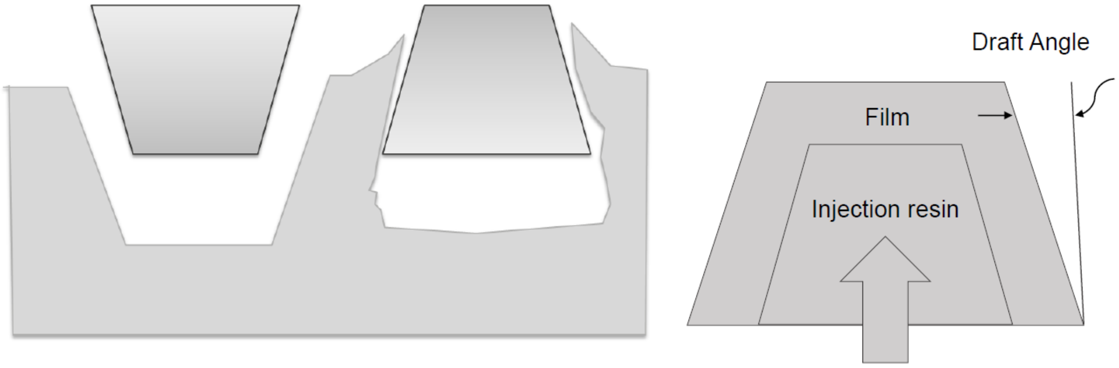
FIM RULE 3

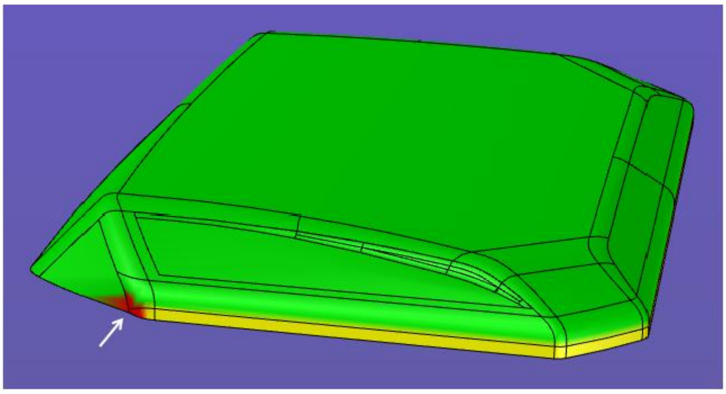
Minimum recommended 2° draft angle, no negative draft angle.



FIM RULE 3

Minimum recommended 2° draft angle, no negative draft angle.

- Negative draft found near some of the edges, may induce issues in forming.

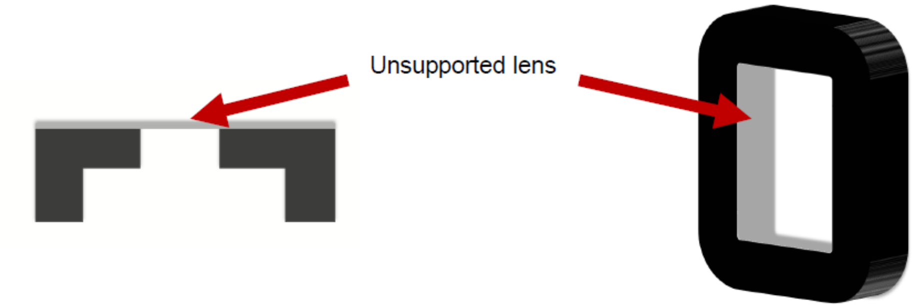


Draft Angle (degree) key: -2.00 -1.00 0.00 1.00 2.00

FIM RULE 4

No unsupported lens areas.

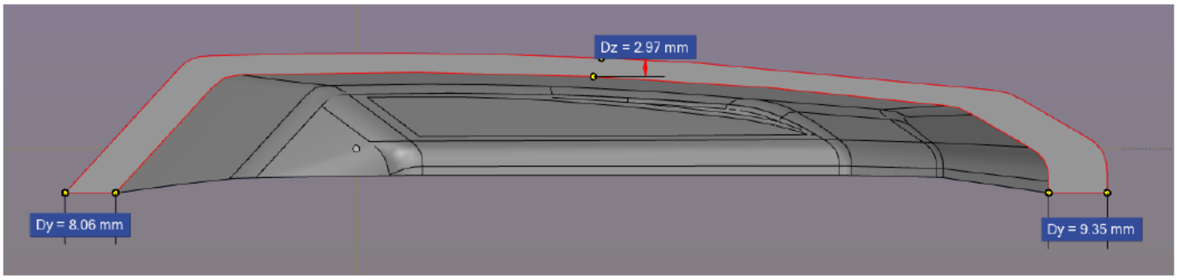
- A two-shot mold with clear resin to support the lens is recommended.
- Unmolded, unsupported, lenses and windows must be avoided, and are not recommended due to the support of the lens or window, and to prevent mold sink.



FIM RULE 4

No unsupported lens areas.

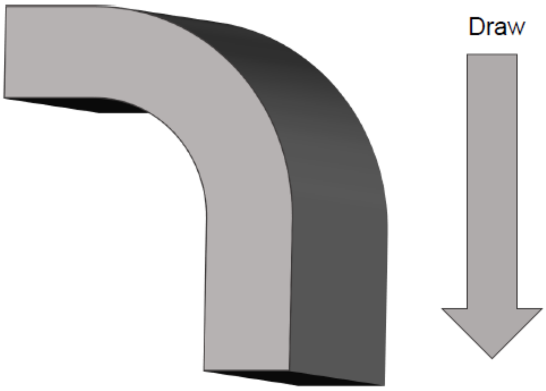
- No unsupported region found.



FIM RULE 5

Maximum draw is film and sheet size specific.

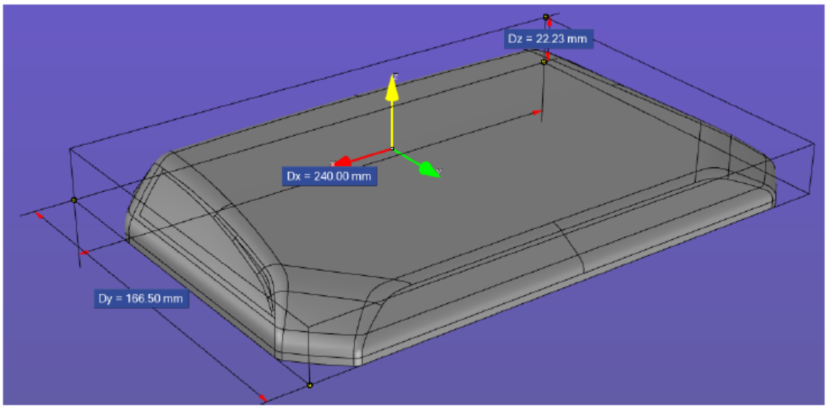
- Maximum draw is defined by % reduction in film thickness.



FIM RULE 5

Maximum draw is film and sheet size specific.

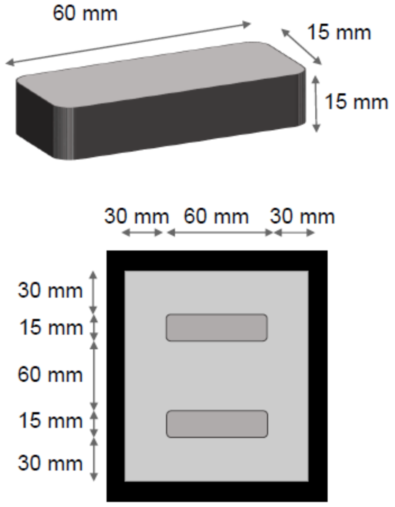
- The depth of draw of the cover part was measured to be less than 23 mm and is achievable with XtraForm 250.



FIM RULE 6

Pack Density is product specific see data sheets.

- Follow the rule of 2 times the draw depth between the part and the forming clamp.
- When applicable, follow the rule of 4 times the draw depth between parts, if multiple parts are nested on a single sheet.
- Pack density rules have been developed to ensure optimum use of material.
- Example, part size 60 mm x 15 mm with a draw depth of 15 mm.
- Distance between part and forming clamp must be ≥ 2 x 15 mm = 30 mm.
- Distance between parts be ≥ 4 x 15 mm = 60 mm.
- Tooling design needs to be feasible.
- MAES can review tool design to ensure pack density rules are adhered too prior to tool design approval before manufacture.



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FIM RULE 7

No first surface forming contact with XtraForm.

- The XtraForm hardcoat is soft before cure and can be damaged by first surface contact.
- High pressure forming equipment for FIM is recommended.
- High pressure forming will ensure a consistent and undisturbed texture when forming XtraForm Antiglare or XtraForm Lacquers.
- Niebling offer a variety of high-pressure forming machines such as the SAMK400 & 650 and HPF1400 with varying levels of film and part size as well as depth of draw capabilities, refer to literature for further information.

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FORMING CONSIDERATION

Forming options for part.

- XtraForm Gloss is recommended to maintain at least 50% of original film thickness during the forming process.
- XtraForm Antiglare is recommended to maintain at least 60% of original film thickness during the forming process.
- For an ideal registration of the graphics, Niebling recommend keeping the film sheet size as small as possible.
- Draw depth is part design, film, sheet size and forming equipment specific.
- Registration of finished FIM parts made with Niebling forming equipment could be as close as ±0.2 mm.
- MacDermid cannot make the commitment on tolerance for our suppliers, and each FIM processor will need to quote their own tolerance based on their own processes and internal capabilities.
- Tool design must accommodate the thickness of both the film and the printed ink and the printed texture if relevant.
- It is recommended single sourcing the FIM tooling suite to ensure consistent geometry at forming, cutting and molding.
- Thermal camera systems to monitor forming temperatures and in line registration measurement are highly recommended.

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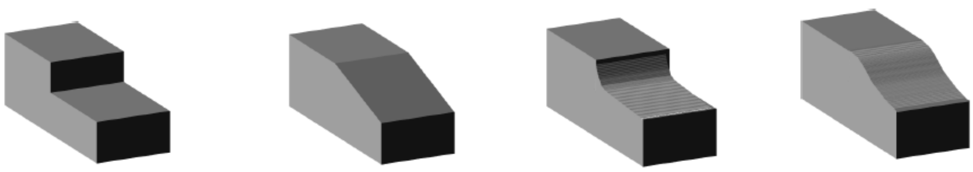
FIM RULE 8

Changes in mold thickness should be avoided especially close to graphics (cause of ink wash).

- FIM parts for automotive applications using PC PC/ABS resin are typically ≥ 2.5 mm thick, they should never be <1 mm.
- Consistent wall thickness will reduce the risk of ink wash and A surface defects in the part.
- Clips and fixtures on the reverse of the part may cause problems.
- If variation in thickness is a necessity, a gradual change rather than a step change would be recommended.



Incorrect   Correct   Incorrect   Correct

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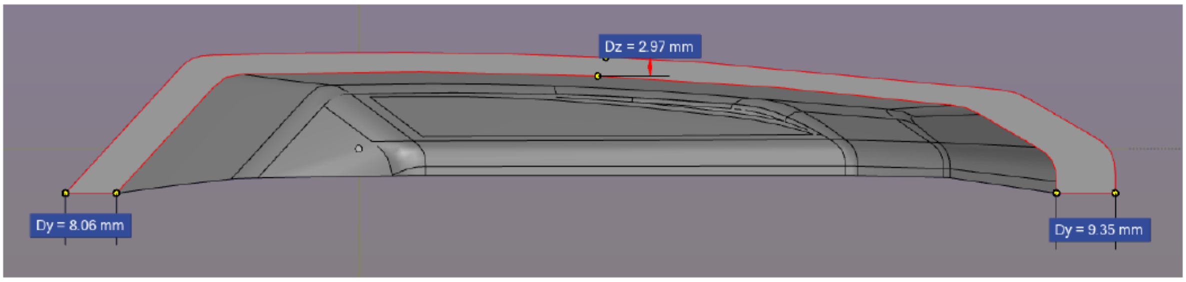
FIM RULE 8

Changes in mold thickness should be avoided especially close to graphics (cause of ink wash).

- No issue found for mold thickness.
- The thickness of the part is between 3 to 9 mm. If no molding is intended, then this thickness is much higher than what we expect.



MOLDING CONSIDERATION

Resin.

- Resin Choice.
  - Automotive applications typically use resins that are PC or PC/ABS.
  - XtraForm Gloss and XtraForm Antiglare are PC based films and are typically molded with PC resin when used in automotive applications.
  - A resin with a low viscosity plus the required impact / flex modulus and other characteristics, should be utilized.
  - Moldflow analysis is highly recommended with a competent moldflow provider.
  - XtraForm can be used in many applications with a variety of alternative resins.
  - XtraForm can be molded with PMMA resin, but an adhesion promoter layer will be required.
- One or Two shot mold.
  - The part appears to be a one-shot mold. A two-shot mold more easily manages light leaks from back lit electronics and reduces the possibility of A surface defects.
  - The first shot would be to freeze the aesthetics of the full part and provide rigidity to the part.
  - The second shot would be to provide the light guides, rear features, and final structure for snapping the part into the final assembly.
  - MAES recommend that tool suppliers have close co-operation and open discussions between all toolmakers / suppliers regarding final part geometry required, shrink rate and part geometry for forming, cutting and molding tools.

MOLDING CONSIDERATION

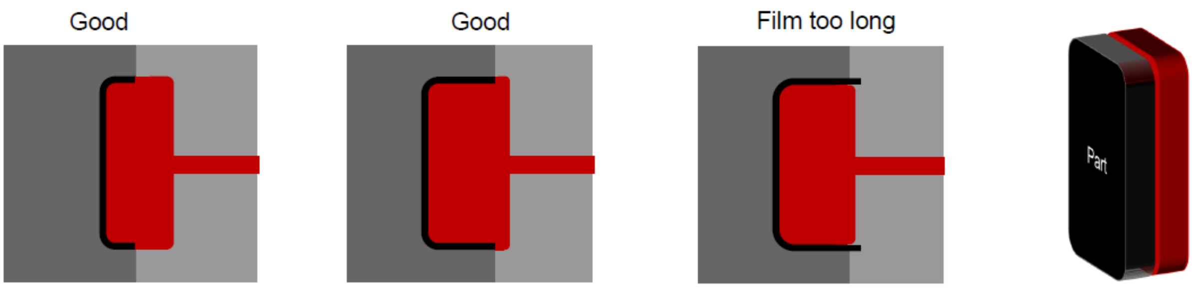
Gating.

- The gates should be placed away from graphic areas to prevent ink wash.
- Gating should be adjacent to any feature bar, so the resin flow is parallel with the bar.
- Consult the tooling manufacturer in order to create gates that are engineered to avoid ink wash.
- Moldflow should be completed as part of the DFM process, prior to manufacturing of any tool to achieve the optimal injection process for shear rates, shear stress and pressure.
- Gates should be designed to allow the best flow and pressure characteristics, identified and optimised from the moldflow analysis.

FIM RULE 9

Parting line needs to be situated to allow the positioning of the film in the tool.

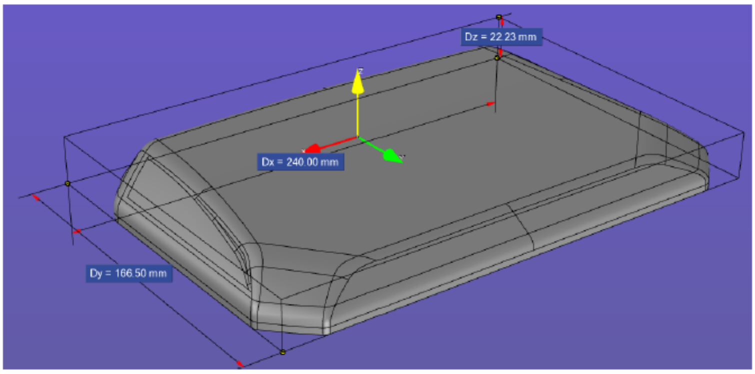
- Do not mold with the film past the parting line.
- If the film is too long, it can damage the tool.
- If the cavity is to shallow the film can fall out.



FIM RULE 9

Parting line needs to be situated to allow the positioning of the film in the tool.

- NA. No film layer is found in the CAD file.



FIM RULE 10

Registration requirements considered and achievable – supplier specific

- Registration tolerance is supplier specific so should be discussed with individual suppliers, but graphics should not be placed in areas of high draw, i.e. sidewalls.
- For an ideal registration of the graphics, Niebling recommend keeping the film sheet size as small as possible.

ADDITIONAL CONSIDERATION

FIM Ink System and Decoration.

- The gates should be placed away from graphic areas to prevent ink wash
- XtraForm films are clear and are decorated on the B-Surface providing protection of decorative and graphic areas.
- A suitable FIM graphic ink system should be used.
- A low conductive carbon ink will be recommended for capacitive touch requirements.
- A two-component FIM ink could be used for added resistance to ink wash.
- Film insert molding offers the ability to run multiple graphics on one tooling set with low MOQs.
- Dead front/Secret-till-lit graphics are possible with FIM, and the requirement must be discussed with your FIM processor who can determine the correct inks for dead front graphics and resin compatibility.

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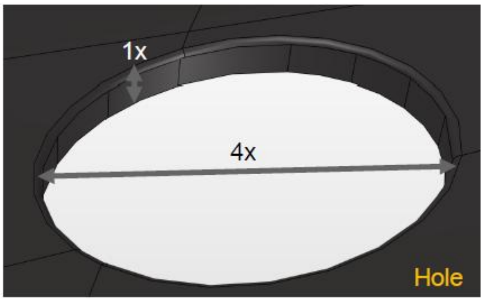
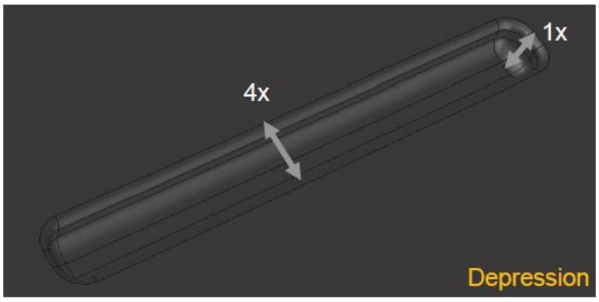
FIM RULE 11

Holes & depressions within a part need to be 25% or less in depth than their narrowest width.

- Must also meet FIM Rule 2, 3 & 6





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FIM RULE 11

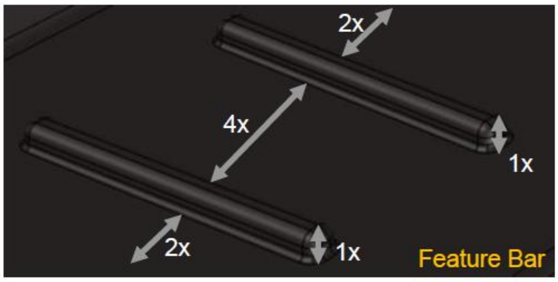
Holes & depressions within a part need to be 25% or less in depth than their narrowest width.

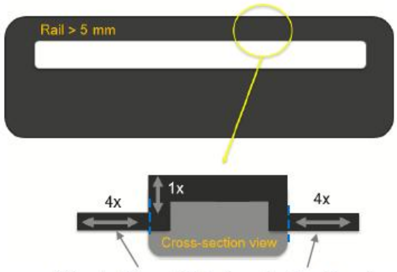
- NA

FIM RULE 12

Length of film between feature bars & rails within a part need to be at least 4 times their height

- Rails & feature bars will need to register perfectly in the mold tool, or the cured XtraForm film will be reshaped or changed in the molding process.
- FIM Rule 6 needs to be applied between rails and for multiple feature bars.





Waste film which is cut after forming

FIM RULE 12

Length of film between feature bars & rails within a part need to be at least 4 times their height

- NA

FIM RULE 12

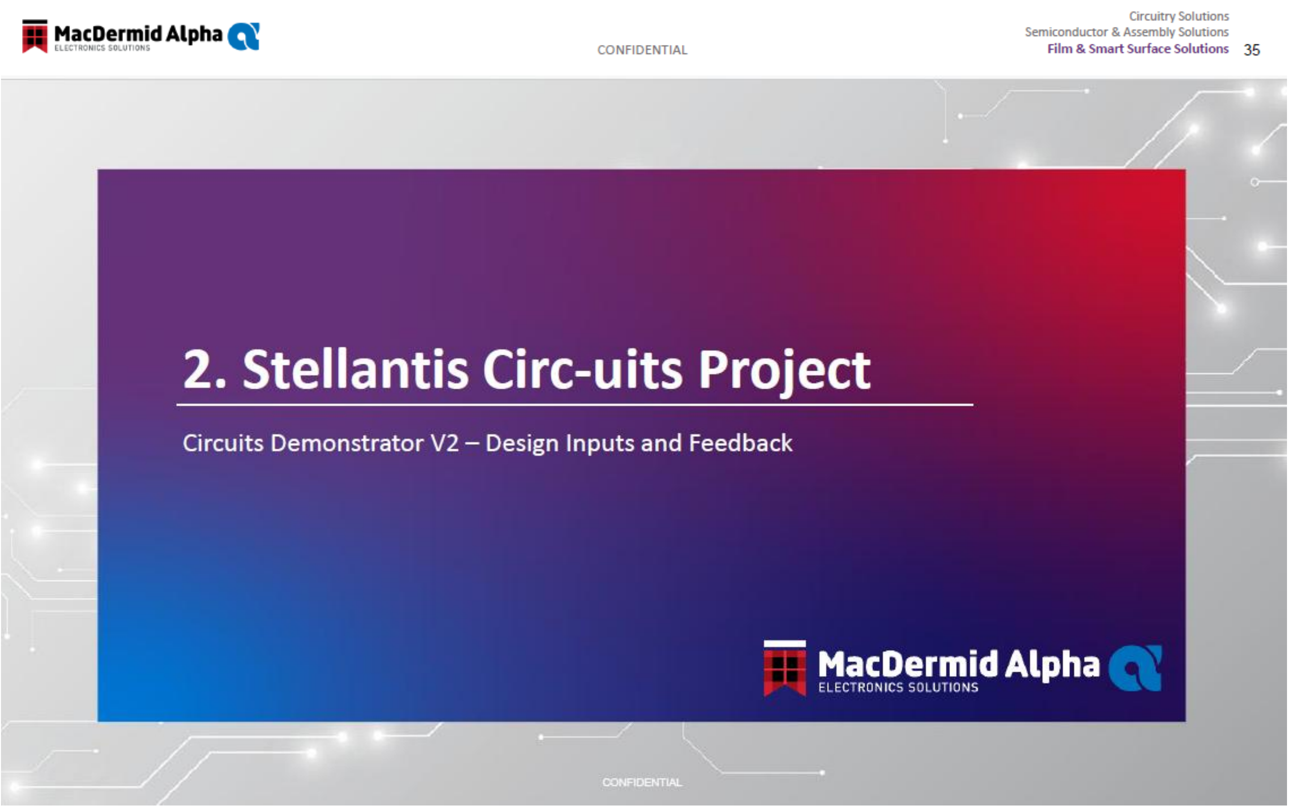
Features.

- Thin raised features are difficult to reproduce with FIM and are considered high risk features.
- Registration of the part in the mold tool is critical.
- Proximity of raised features to each other could also lead to cracking.
- Reshaping a FIM part may cause the UV cured hardcoat to crack and introduce hardcoat flakes into the mold tool.
- The introduction of hardcoat flakes in the tool at every mold shot will cause pit marks in the A-surface of the part and increase scrap.
- Traditionally, FIM processors require a minimum width of rails 5mm, this should be discussed with the processor.
- MacDermid can support a discussion with the FIM processor and the design responsible party.

ALTERNATIVE SURFACE FEATURES

- **XtraForm Antiglare** hard coated film is available in 15, 35 & 65 GU on a 250 µm PC film.

- **XtraForm Fine & Supermatt**, screen printable textured lacquers, have been designed for selective printing and formulated to be printed directly on the hard coated XtraForm surface. Both can be mixed with a Gloss Modifier to produce areas of low gloss between 1 GU and 35 GU.



Content

1	**Stellantis CIRCUITS Project - FIM Evaluation** ▸ Stellantis Circuits Pilot 3 – Overview & Summary ▸ FIM Rules and Part Overview ▸ Specifications Requirements ▸ Comments on Drawing ▸ FIM Rule 1 to Rule 12 Feedback
2	**Stellantis CIRCUITS Project – Electronic Circuit Evaluation** ▸ Stellantis Circuits Demonstrator V2 Overview ▸ Circuits Demonstrator V2 – Graphic Layers ▸ Circuits Demonstrator V2 – Printed Silver Inks & Requirements ▸ Circuits Demonstrator V2 – Formability Inputs ▸ Summary

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Inputs and Review of Circuits Demonstrator V2:

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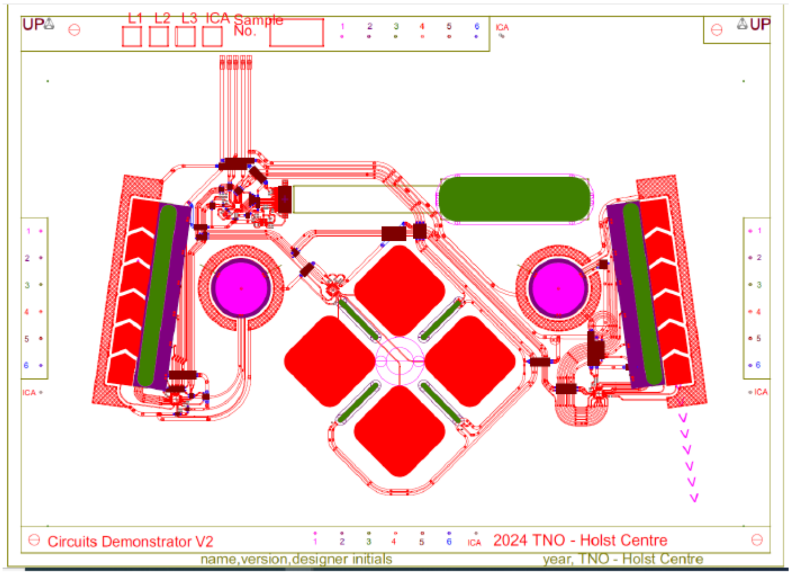
Circuits Demonstrator V2 - Overview



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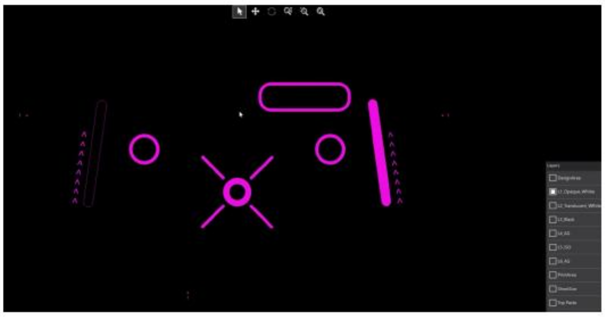
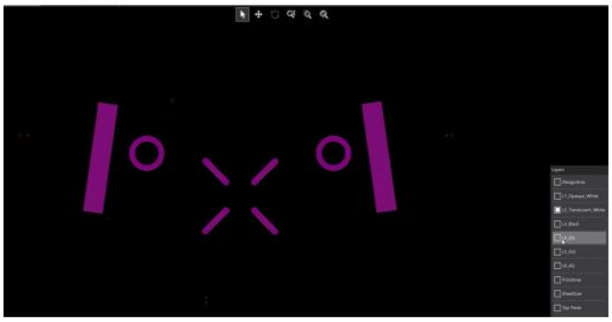
Circuits Demonstrator V2 – Graphic Layer 1 & Layer 2

L1: Opaque White	L2: Translucent White
	

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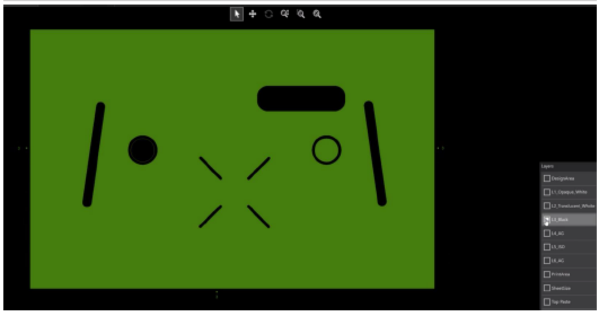
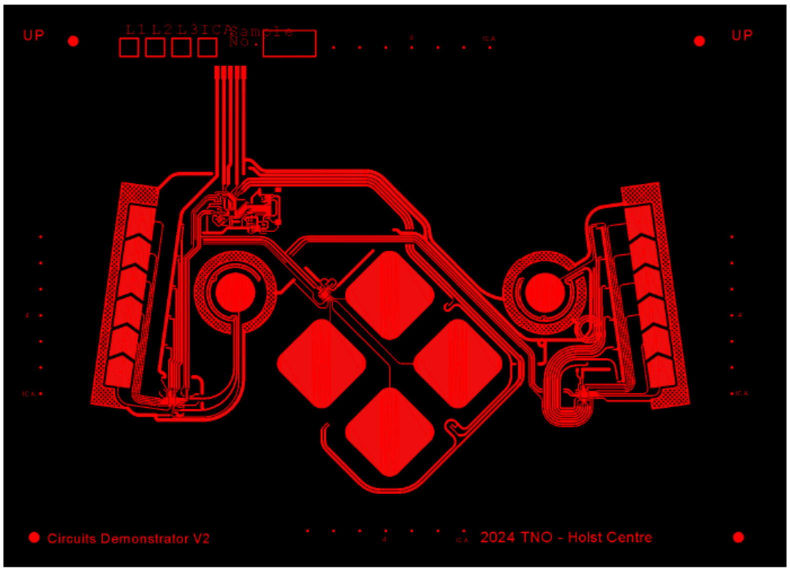
Circuits Demonstrator V2 – Graphic Layer 3

L3: Black



Circuits Demonstrator V2 – Printed Silver Ink – Layer 4



Circuits Demonstrator V2 – Printed Silver Ink – Layer 4

Printed Silver Line Width & Line Gap Review

Features	Minimum / Smallest Design Features (in microns)	Maximum Design Size / Features (in microns)
Line width	300	1200
Line Gap	200	1350

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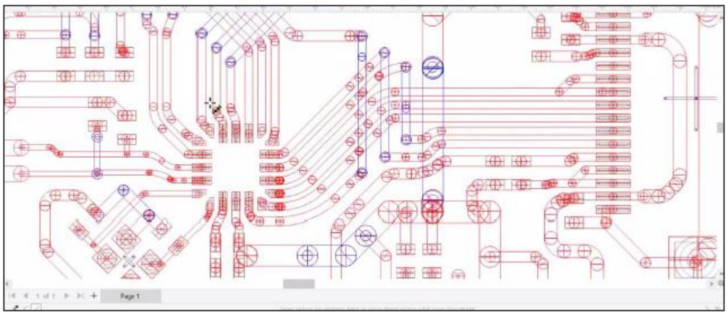
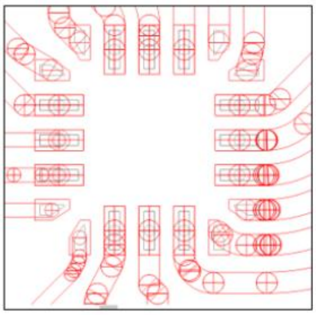
Processor Pad Review:

Three Processors for handling individual / local inputs





Processor Features	Minimum / Smallest Design Features (in microns)	Maximum Design Size / Features (in microns)
Pad Width	300	NA
Pad Gap	200	NA

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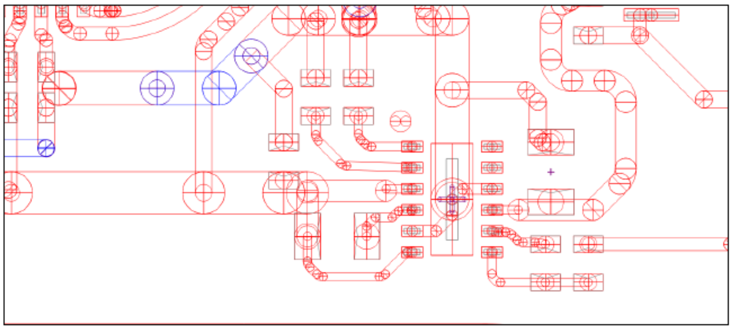
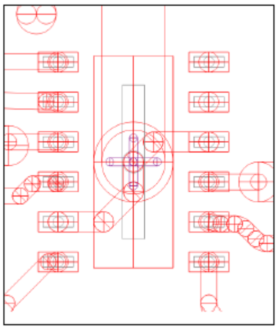
IC Pad Review:





Processor Features	Minimum / Smallest Design Features (in microns)	Maximum Design Size / Features (in microns)
Pad Width	250	NA
Pad Gap	250	NA

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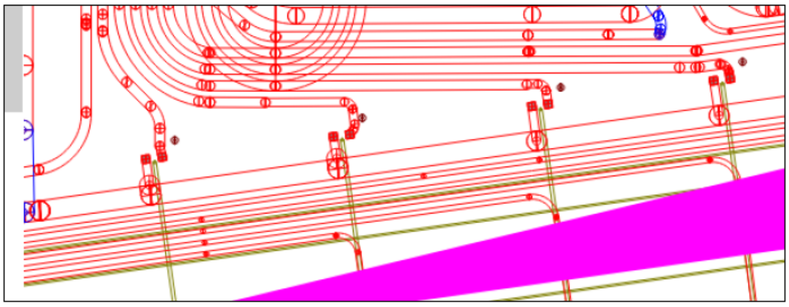
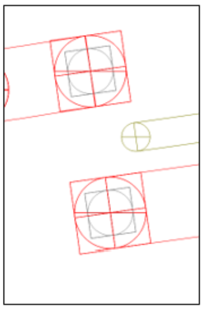
LED Pad Review:





LED Features	Minimum / Smallest Design Features (in microns)	Maximum Design Size / Features (in microns)
Pad Width	500	500
Pad Gap	500	500

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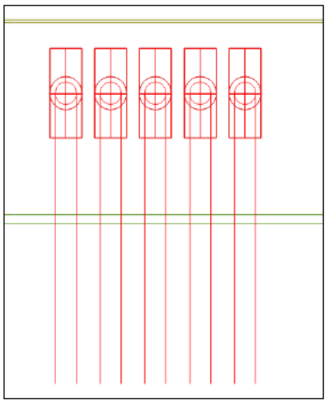
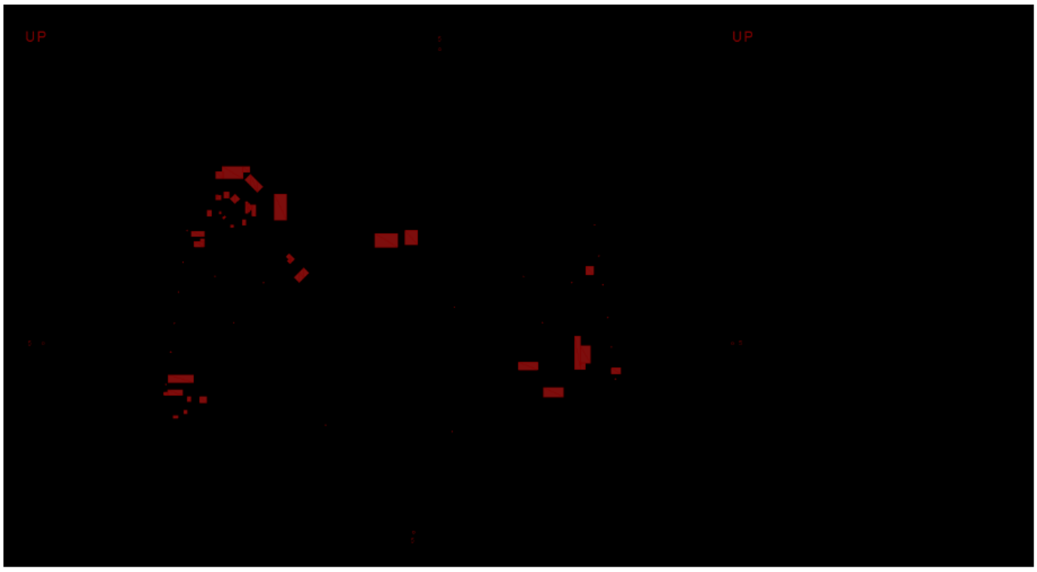
Connector Review:

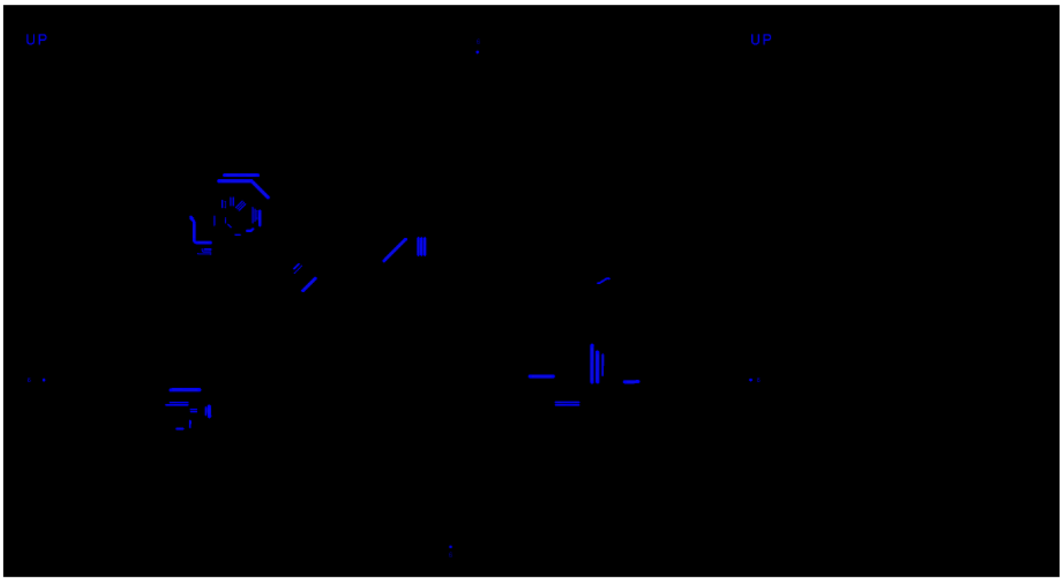


LED Features	In Microns
Pad Width	1800
Pad Pitch	2540
Pad Gap	740

Circuits Demonstrator V2 – Layer 5 (Dielectric Layer)



Circuits Demonstrator V2 – Layer 6 (Silver Ink)

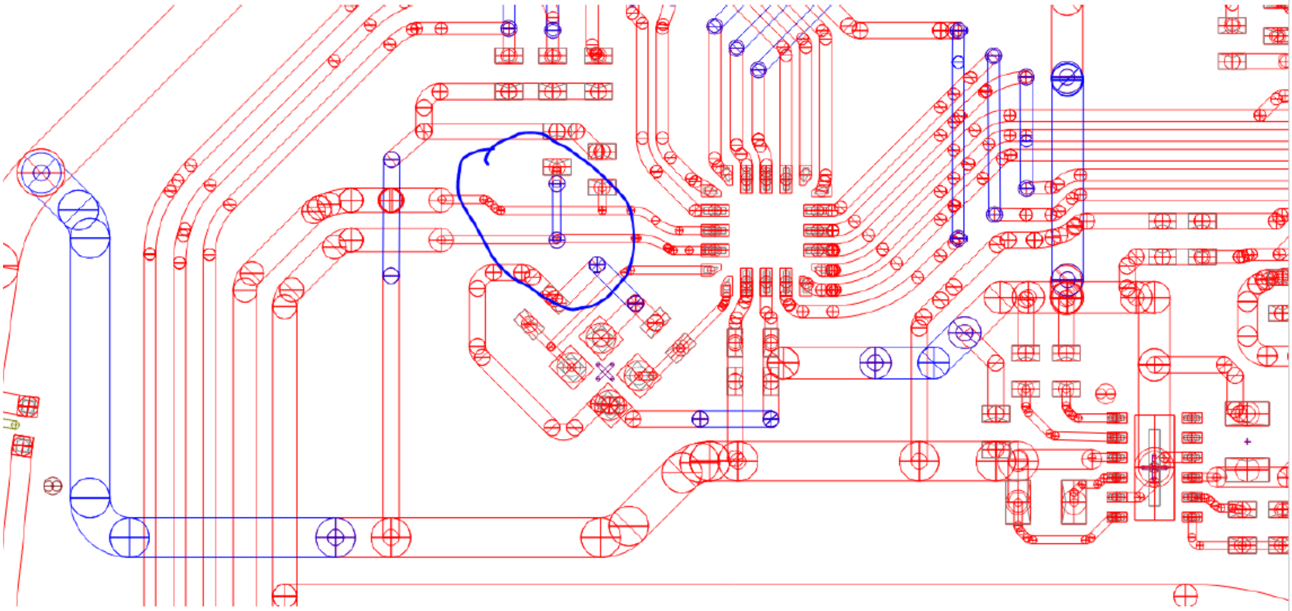


Circuits Demonstrator V2 – Printed Silver Ink – Layer 6

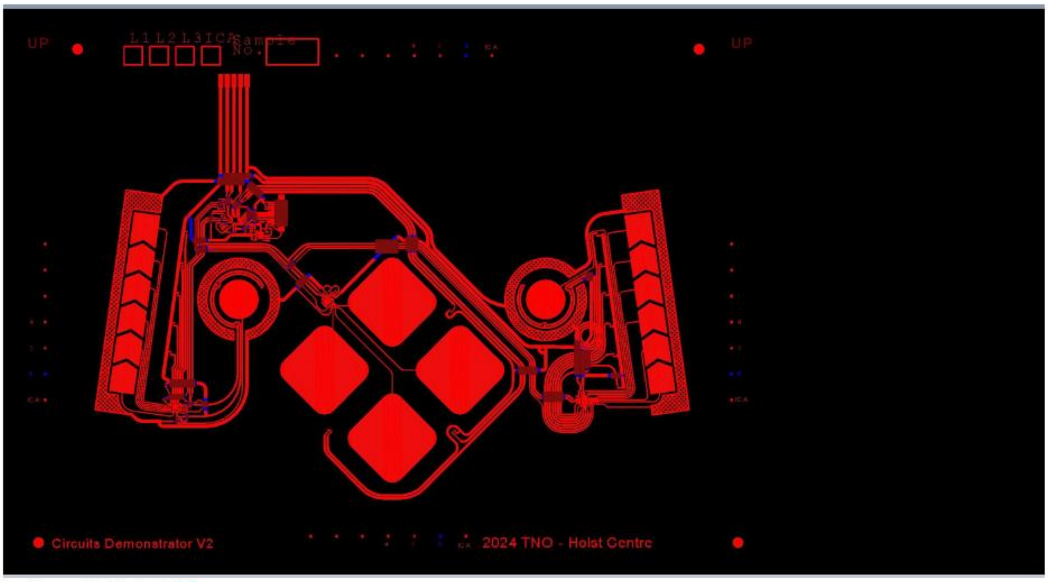
Printed Silver Line Width Review. Lien Gaps for Cross over Silver Not Applicable

Features	Minimum / Smallest Design Features (in microns)	Maximum Design Size / Features (in microns)
Line width	300	1200
Line width	200 [Noticed 200-micron line width only at one place. Refer image on next slide.]	1200
Line Gap	NA	NA

Cross-Over Silver 200-micron line



Circuits Demonstrator V2 – Layer 4 to L6 Overlayed



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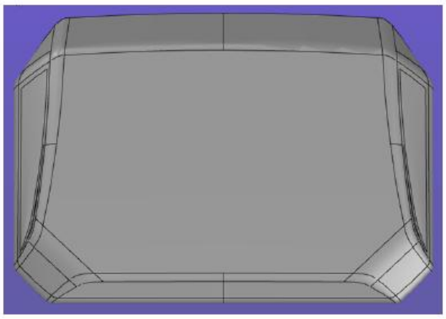
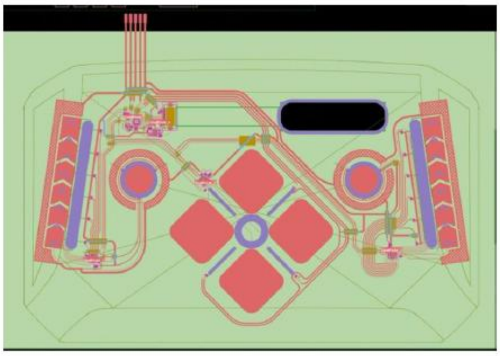
Curcuits Demonstrator V2

Surface A and Surface B (Electronic Circuit Side)





- Most of the electronic circuit seems to be on flat film (minimal to no forming).
- Silver Inks printed on capacitive sliders will go through mild forming.
- Silver Inks on tail part will be subject to most forming.

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Summary

- This Circuits Demonstrator V2 review was undertaken for Printed Silver Circuit requirements.
- For Circuits - Line Widths and Tracks are acceptable.
- Further Dielectric and Cross Over Silver Circuits were also reviewed.
- Silver Inks are subjected to minimal forming.
- This review mainly covered printing aspects and not the full functionality of the actual circuit.

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8.2 Annex B

Description of the Current Sorting Process

The material sorting process intended for the foundry is based on a careful selection of electronic boards, which are categorized according to their precious metal content. This allows for an accurate estimation of the economic yield of the materials sent.

Generally, the batches sent range from 500 kg to 5 tons, with an estimated gold concentration between 70 and 85 ppm per ton (0.0070-0.0080 wt%). The estimated value of the materials, such as gold, silver, palladium, and copper, is calculated at the time of shipment by comparing internal valuations with those of the foundry and the market value of the materials at that historical moment.

In addition to the stated values for gold (70–85 ppm per ton), similar estimates can be provided for other precious metals. Below is a summary of the main materials:

- **Silver**: ranges from 700 to 1000 ppm.
- **Copper**: generally between 170 and 200 kg per ton.
- **Palladium**: between 10 and 30 ppm depending on the type of board.

The quantity of these metals is calculated based on two values:

1. Absolute value (ppm – parts per million).
2. Value relative to the total weight of the material sent. For example, if an 80 ppm gold concentration is estimated and 2 tons of material are sent, the total gold will be 160 ppm. (1 ppm = 1 kg/ton.)

The facility preparing to send the material to the foundry estimates the value of the batch (e.g., €5,838) and later receives a settlement based on the foundry's analysis (e.g., €5,450 instead of €5,838). The discrepancy in valuation is not solely the responsibility of the manual selection performed by the operators, who may err in recognizing the type of board. The batches sent are organized according to categories identified by the facility, and thus include a variety of heterogeneous boards, which can affect the estimation of the content of critical raw materials.

The categorization by the facility arises from a "learning-by-doing" process in which the operators have performed the sorting operation countless times until they understood the necessary actions to achieve consistent economic estimates for the batches; currently, the facility claims to have found a selection balance that allows for an efficiency estimation of 97%. This compliance represents adherence to selection expectations, namely the target/economic value to be achieved through selection.

Second choice PCBs values –"learning-by-doing" process

Below is an example of yield in terms of precious metals for various batches of second-choice boards, sent on different dates:

Day	Silver (ppm)	Gold (ppm)	Copper (kg/ton)	Palladium (ppm)	Euro (€)
29/04/2022	788	82	198.6	10	4.339
29/04/2022	1018	104	191.4	32	5.648
16/06/2022	687	68	193.5	8	3.469

Day	Silver (ppm)	Gold (ppm)	Copper (kg/ton)	Palladium (ppm)	Euro (€)
16/06/2022	921	91	201.6	29	5.181
10/08/2022	796	93	201.2	13	4.643
10/08/2022	952	96	203.4	20	4.377
30/11/2022	836	103	200	27	5.548
08/02/2023	643	57	178.2	5	2.402
20/02/2023	702	63	172.5	8	3.067
20/02/2023	706	67	176.5	12	3.205
20/02/2023	823	81	168.6	22	4.456
16/04/2023	921	94	183	22	5.155
Media	816	83	189	17	4.291

After sending 12 batches, the average yields obtained provide a reliable reference for future shipments, allowing for predictions of yields based on the composition of the batches and the value of the metals at the time of shipment.

PCBs categories

For the purposes of the project, the electronic boards have been divided into four macro-categories: very high value, high value, medium value, and low value, depending on the presence of certain components and materials, substrate color, shape, and size.

The recognition criteria adopted by the facility are summarized in the attached Excel file, which outlines the types of boards processed and the basis for the selection process: OT boards (very high value), old-generation PC boards, old-generation server boards, new-generation server boards, and notebook boards (high value); new-generation PC boards (medium value); and third-choice boards (low value). Therefore, the information should not be considered exhaustive or applicable to any type of board.

By integrating the facility's information with literature data, it is possible to develop a more comprehensive model for defining categories, as proposed below:

- **First-choice boards – Very High & High Value**
  - **Mobile phone boards**
  - **Hard disk boards**
  - **First choice back panels**
  - **First choice OT boards**
  - **First choice peripheral boards**
  - **Old-generation first-choice boards**
  - **New-generation first-choice boards**
  - **First super high yield boards**
- **Second-choice boards – Medium Value**
- **Third-choice boards – Low Value**

Here is a description of the categories of boards used by the facility, based on the intrinsic characteristics of the boards themselves and their precious metal content. These data are gathered from previous findings and literature research. All wt% are referred to the weight of the products.

1. Mobile phone boards

- **Description:** Electronic boards primarily sourced from mobile devices such as smartphones and tablets. These boards contain a significant amount of precious metals, including gold, silver, and palladium, as mobile devices require high-quality electronic connectivity in a compact format; they add up to 18wt% of the phones.
- **Main Metals**: Gold, copper, palladium, silver.
- **Critical Materials:** They contain precious metals such as gold (in connectors), silver (in electrical contacts), copper (in circuit traces), palladium (in capacitors), and rare earth elements in components like microprocessors and screens.

- Gold: 0.01–0.05 wt%.
- Silver: 0.01–0.03 wt%.
- Palladium: 0.001–0.01 wt%.
- Copper: 15–20 wt%.
- Rare earths (Neodymium, Dysprosium, Terbium): 0.01–0.03 wt% (in magnets for motors and sensors).

• **PCB Components:** Microprocessors, displays, wireless antennas, MLCC capacitors, flash memory.

2. Hard Disk boards

- **Description:** Electronic boards sourced from hard disk drives (HDD) and storage units. These boards have a moderate amount of precious metals and other recoverable materials. They contain control circuits and connectors.
- **Main Metals:** Copper, gold, silver, palladium.
- **Critical Materials:** Copper (wires and circuit traces), gold (in connectors), aluminum (structure and magnetic disks), neodymium (in HDD motor magnets), palladium and silver (in contacts). SSD units may contain more silicon in memory chips.
  - Gold: 0.02–0.05 wt% (gold connectors and contacts).
  - Silver: 0.005–0.02 wt% (in contacts).
  - Palladium: 0.001–0.01 wt% (in electronic components).
  - Copper: 10–15 wt% (traces and connectors).
  - Rare earths (Neodymium): 0.05–0.1 wt% (in permanent magnets of motors - spindle motor - voice coil motor - VCM).
- **PCB Components:** Memory controllers, SATA or NVMe interfaces, capacitors, interconnection cables.

3. First choice Back Panels

- **Description:** Boards sourced from the back panels of electronic equipment, often part of more complex devices such as servers or networking equipment. These boards are generally of high quality and offer a good amount of recoverable materials.
- **Main Metals:** Copper, gold, palladium.
- **Critical Materials:** High copper content for connections, gold for contacts, silver and palladium in capacitors. They may also include components with rare earth elements like neodymium (in magnets for electric motors and cooling fans).
  - Gold: 0.05–0.1 wt% (in high-quality connectors and contacts).
  - Silver: 0.01–0.03 wt% (in electrical contacts).
  - Palladium: 0.01–0.03 wt% (in MLCC capacitors).
  - Copper: 20–25 wt% (in traces and wiring).

- Rare earths (Neodymium, Dysprosium): 0.01–0.03 wt% (in magnets for motors and fans).

- **PCB Components:** Backplane for network connectivity, expansion interfaces, power supplies, network ports (Ethernet).

4. First choice OT boards

- **Description:** First-class boards derived from telecommunications devices and optical electronic equipment. These boards are classified as "super" due to their high concentration of precious metals, especially gold and copper.
- **Main Metals:** Gold, copper, silver.
- **Critical Materials:** Gold (in connectors), palladium (in electronic components), copper (in circuit traces), erbium and other rare earth elements used for optical amplifiers and transmission devices. Fiber optic components may include materials like silicon in photonic chips.
  - Gold: 0.03–0.06 wt% (in contacts and connectors).
  - Silver: 0.01–0.03 wt% (in contacts).
  - Palladium: 0.005–0.02 wt% (in capacitors).
  - Copper: 15–20 wt% (in traces and wiring).
  - Rare earths (Erbium): 0.005–0.01 wt% (in optical amplification components).
- **PCB Components:** Optical network modules, amplifiers, transmission/retransmission circuits, fiber optics.

5. First choice peripheral choice

- **Description:** Boards sourced from peripheral devices such as printers, scanners, and keyboards. These boards contain smaller amounts of precious metals compared to other "super" boards, but their quality makes them valuable for recovery.
- **Main Metals:** Copper, gold, silver.
- **Critical Materials:** Copper (connection cables and traces), gold (in contacts), silver and palladium in electronic components. Some printers and monitors may contain small amounts of indium in LCD screens.
  - Gold: 0.02–0.05 wt% (in contacts).
  - Silver: 0.01–0.02 wt% (in electrical contacts).
  - Palladium: 0.001–0.01 wt% (in electronic components).
  - Copper: 10–15 wt% (in traces and connectors).
  - Rare earths (Indium): 0.01–0.02 wt% (in LCD displays).
- **PCB Components:** Control circuits, USB interfaces, power controllers, displays.

6. Old-generation first-choice boards

- **Description:** Boards from older electronic devices that date back to previous technologies. Although older, these boards often contain significant amounts of precious metals, as older devices utilized more robust circuits rich in materials like gold.
- **Main Metals:** Gold, copper, silver, palladium.
- **Critical Materials:** These boards often contain high amounts of copper (traces), gold (contacts and connectors), silver, and palladium (capacitors). Old TVs may contain lead in cables and tin in solder.
    - Gold: 0.05–0.15 wt% (high-quality gold connectors and contacts).
    - Silver: 0.02–0.05 wt% (in contacts and coatings).
    - Palladium: 0.005–0.02 wt% (in capacitors).
    - Copper: 20–30 wt% (in traces and connectors).
    - Rare earths: Minimal traces, generally absent in older boards.
- **PCB Components:** Microprocessors, RAM, power supplies, pin connectors, electrical cables.

7. New-generation first-choice boards

- **Description:** Boards from next-generation electronic devices, newer and with a different composition compared to older generations. These boards tend to be more efficient in material usage, with significant amounts of precious metals.
- **Main Metals:** Copper, gold, palladium.
- **Critical Materials:** Gold (connections and contacts), copper (traces and wires), palladium and silver (electronic components). These boards may also include components with rare earth elements such as dysprosium and neodymium in motors and magnets.
    - Gold: 0.03–0.07 wt% (in connectors and contacts).
    - Silver: 0.01–0.03 wt% (in contacts and wiring).
    - Palladium: 0.003–0.02 wt% (in MLCC capacitors).
    - Copper: 15–25 wt% (in traces and wiring).
    - Rare earths (Neodymium, Dysprosium): 0.01–0.03 wt% (in magnets of electronic components and motors).
- **PCB Components:** Advanced microprocessors, graphics cards, USB-C and HDMI connectors, power supplies.

8. First super high yield boards

- **Description**: High-quality boards that ensure a high yield in terms of precious metal recovery. These boards belong to advanced and technologically complex devices, featuring a high concentration of gold, palladium, and copper.
- **Main Metals**: Gold, copper, palladium, silver.

- **Critical Materials**: Gold (in contacts and connectors), copper (traces and wires), palladium and platinum (precision electronic components), rare earths (in sensors and motors). Medical equipment may include significant amounts of platinum and iridium.
    - Gold: 0.05–0.1 wt% (high-quality connectors and advanced circuits).
    - Silver: 0.02–0.04 wt% (in contacts and coatings).
    - Palladium: 0.01–0.03 wt% (in capacitors and precision electronic components).
    - Copper: 20–30 wt% (in traces and connectors).
    - Rare earths (Platinum, Iridium): 0.01–0.02 wt% (in sensors and advanced medical instruments).
- **PCB Components**: Advanced microprocessors, high-capacity memory modules, cooling systems, network connectors.

9. Second-choice boards – Medium Value

- **Description:** Boards containing fewer precious metals compared to first-choice categories. They come from common or less complex electronic devices. Although of lower quality than first-choice boards, they still have significant recovery value.
- **Main Metals:** Copper, gold, silver.
- **Critical Materials:** Gold (in connectors), copper (in circuits), palladium and silver (in electronic components). Flat-screen TVs may contain indium in the displays.
    - Gold: 0.01–0.03 wt% (in contacts and connectors).
    - Silver: 0.01–0.02 wt% (in contacts and wiring).
    - Palladium: 0.001–0.01 wt% (in electronic components).
    - Copper: 10–15 wt% (in traces and connectors).
    - Rare earths: Minimal traces or absent.
- **PCB Components:** Video control boards, HDMI interfaces, power supplies, memory modules.

10. Third-choice boards – Low Value

- **Description**: Boards of lower quality than second-choice boards, containing a lesser concentration of precious metals. They come from low-end devices or less sophisticated electronic components.
- **Main Metals**: Copper, with small amounts of gold and silver.
- **Critical Materials**: Mainly copper (in cables and circuits), small amounts of gold (in connectors) and silver (in contacts).
    - Gold: 0.005–0.01 wt% (in low-quality connectors).
    - Silver: 0.005–0.01 wt% (in contacts).

- Palladium: Traces, less than 0.001 wt%.
- Copper: 5–10 wt% (in traces and connectors).
- Rare earths: Practically absent.

- **PCB Components**: Simple control circuits, LED displays, power modules, basic interfaces.

11. Fourth-choice boards

- **Description**: These boards represent the category with the lowest concentration of precious metals. They are generally recovered from less valuable electronic devices or production waste. They are primarily useful for the recovery of copper and other basic materials.
- **Main Metals**: Copper, with small traces of other metals.
- **Critical Materials**: Very small amounts of copper, minor traces of gold and silver, larger quantities of plastic and other common materials.
  - Gold: Traces, less than 0.005 wt%.
  - Silver: Traces, less than 0.005 wt%.
  - Palladium: Minimal traces or absent.
  - Copper: 2–5 wt% (in traces and wiring).
  - Rare earths: Absent.
- **PCB Components**: Simple circuits, LCD displays, basic buttons.

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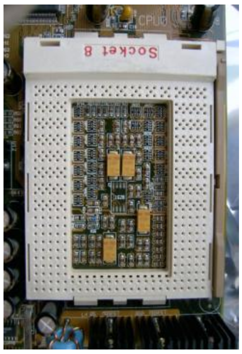
8.3 Annex C

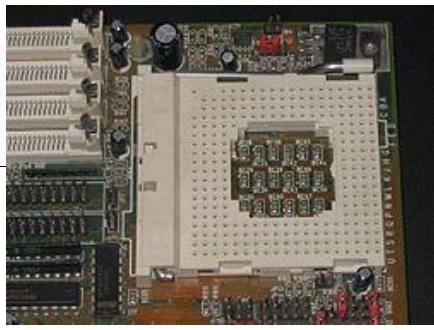
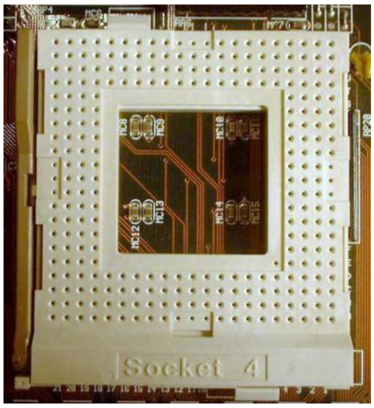
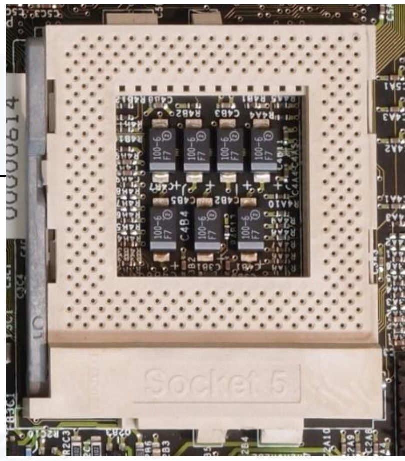
Legacy PC Boards: Manufactured between 1989 and 2001.

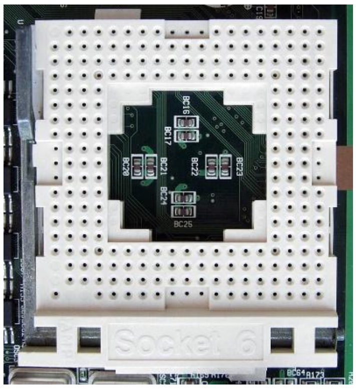
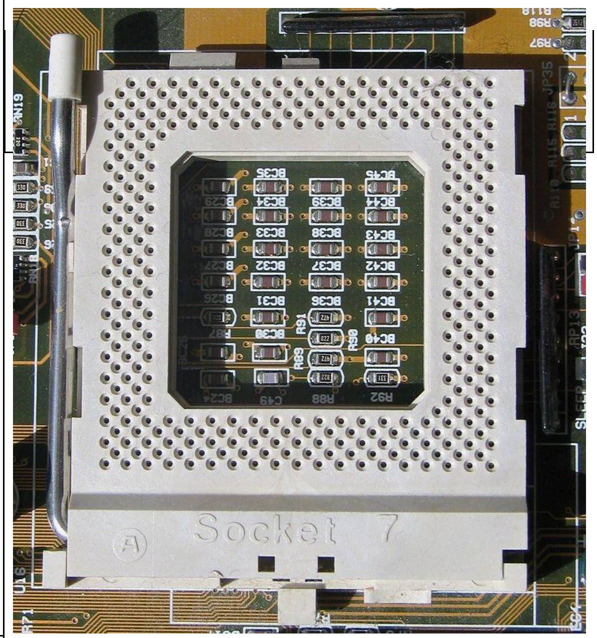
Color: Green or brown.

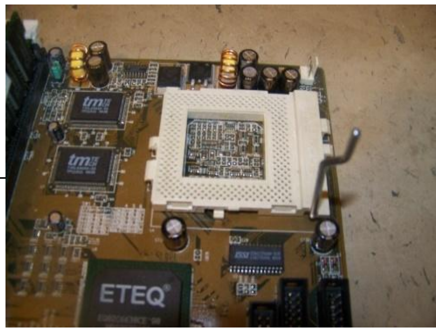
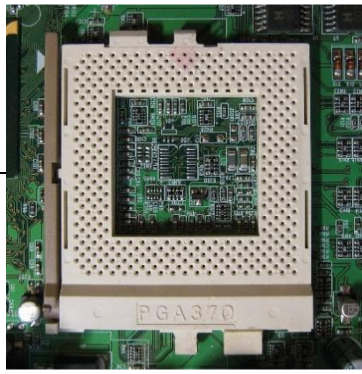
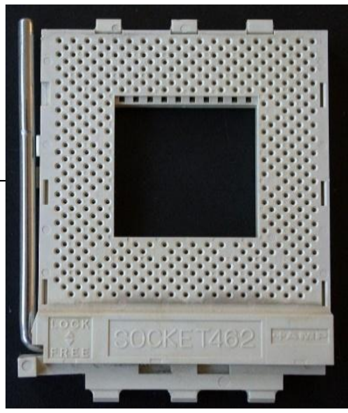
CPU Slot: Includes a dedicated CPU slot, as outlined in the table below.

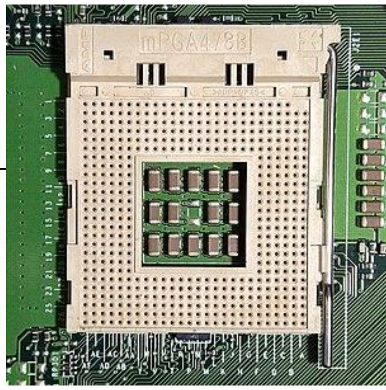
socket name	Year of release	Supported CPU family group	Type of computer	Number of pin	Immage
Socket 8	1995	Intel Pentium Pro	Server	387	
Slot 2	1998	Intel Pentium II Xeon Intel Pentium III Xeon	Server	330	

socket name	Year of release	Supported CPU family group	Type of computer	Number of pin	Immage
Socket 1	1989	Intel 80486 AMD 486 AMD 5x86 Cyrix 486 Cyrix 5x86	Desktop	169	
Socket 2		Intel 80486	Desktop	238	

		Intel Pentium Overdrive (P24T) Intel DX4 AMD 486 AMD 5x86 Cyrix 486 Cyrix 5x86			
Socket 3	1991	Intel 80486 Intel Pentium Overrdrive (P24T) Intel DX4 AMD 486 AMD 5x86 Cyrix 486 Cyrix 5x86 IBM Blue Lightning	Desktop	237	
Socket 4	1993	Intel Pentium	Desktop	273	
Socket 5	1994	Intel Pentium AMD K5 Cyrix 6x86 IDT WinChip C6	Desktop	320	

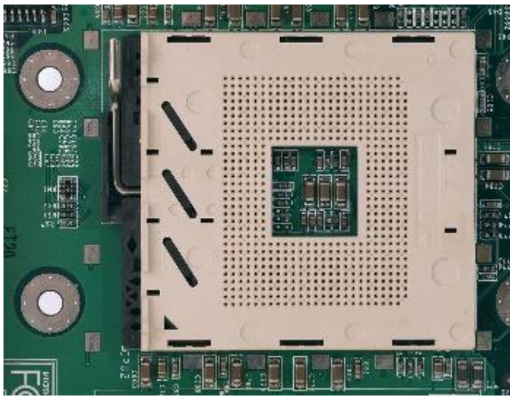
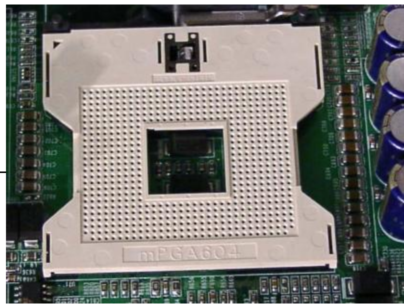
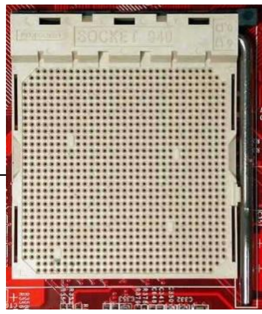
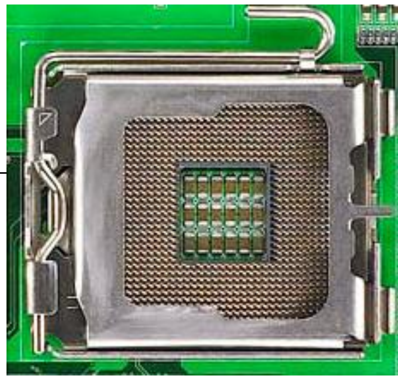
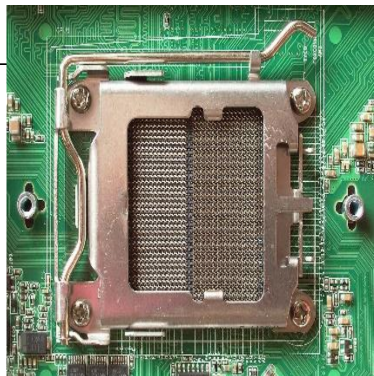
		IDT WinChip 2			
Socket 6	?	Intel 80486	Desktop	235	
Socket 7	1994	Intel Pentium Intel Pentium MMX AMD K6	Desktop	321	
Slot 1	1997	Intel Pentium II Intel Pentium III	Desktop	242	

Super Socket 7	1998	AMD K6-2 AMD K6-III Rise mP6 Cyrix MII	Desktop	321	
Slot A	1999	AMD Athlon	Desktop	242	
Socket 370	1999	Intel Pentium III Intel Celeron VIA Cyrix III VIA C3	Desktop	370	
Socket A/ Socket 462	2000	AMD Athlon AMD Duron AMD Athlon XP AMD Athlon XP-M AMD Athlon MP AMD Sempron	Desktop	462	

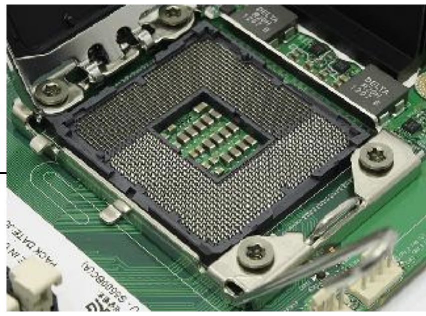
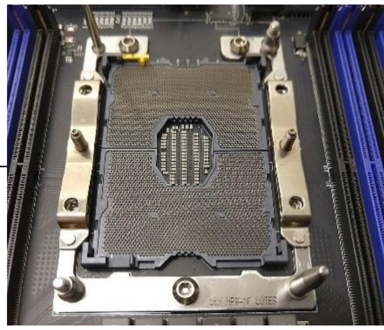
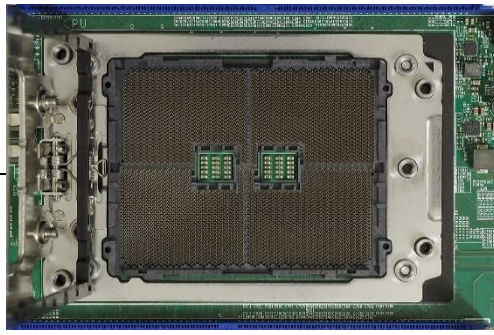
Socket 423	2000	Intel Pentium 4	Desktop	423	
Socket 478/ Socket N	2001	Intel Pentium 4 Intel Celeron Intel Pentium 4 EE Intel Pentium 4 M	Desktop	478	

Legacy PC Boards: Produced between 1989 and
Color: Typically green or
CPU Slot: Features a dedicated CPU slot, as indicated in the table below.

socket name	Year of release	Supported CPU family group	Type of computer	Number of pin	Immage

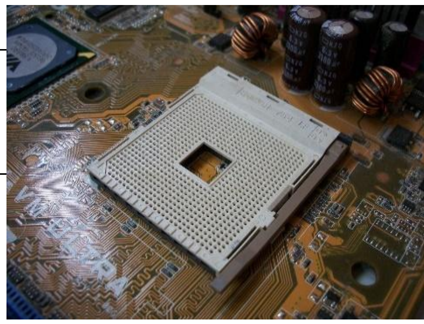
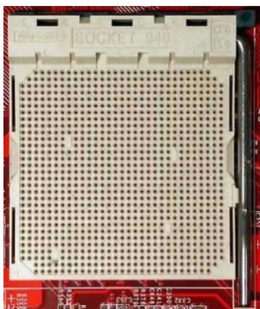
Socket 603	2001	Intel Xeon	Server	603	
Socket 604	2002	Intel Xeon	Server	604	
Socket 940	2003	AMD Opteron AMD Athlon 64 FX	Server	940	
LGA 771/ Socket J	2006	Intel Xeon	Server	771	
Socket F/	2006	AMD Athlon 64 FX	Server	1207	

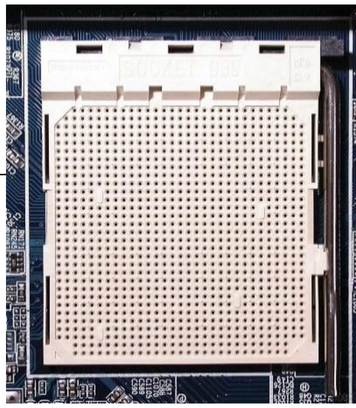
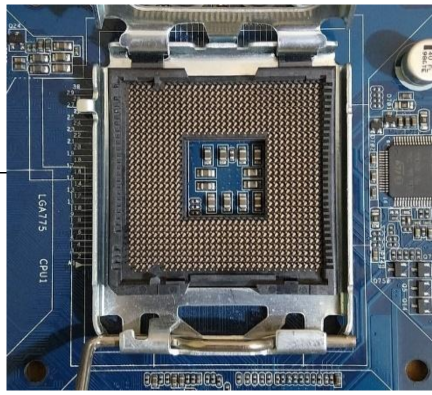
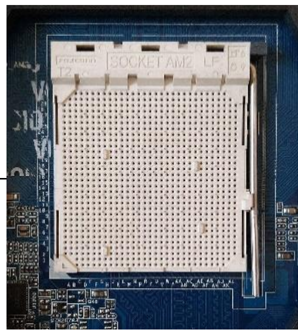
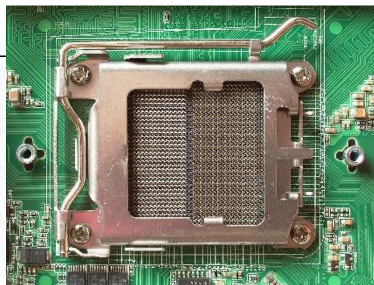
Socket L (**Socket 1207FX**)		AMD Opteron			-
LGA 1366/	2008	Intel Core i7 (900 series)	Server	1366	
Socket B		Intel Xeon (35xx, 36xx, 55xx, 56xx series)			
Socket G34	2010	AMD Opteron (6000 series)	Server	1974	
Socket C32	2010	AMD Opteron (4000 series)	Server	1207	
LGA 2011/	2011/Q3	Intel Core i7 3xxx Sandy Bridge-E	Server	2011	

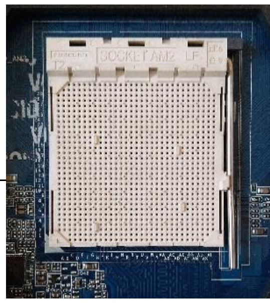
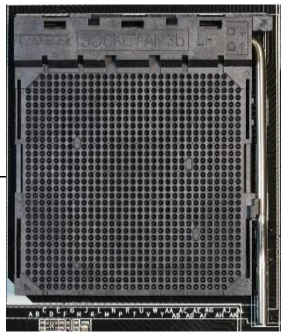
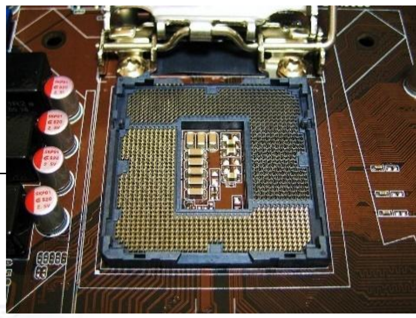
Socket R	2011.11.14	Intel Core i7 4xxx Ivy Bridge-E			-
		Intel Xeon E5 2xxx/4xxx (Sandy Bridge EP) (2/4S)			
		Intel Xeon E5-2xxx/4xxx v2 (Ivy Bridge EP) (2/4S)			
LGA 1356/ Socket B2	2012	Intel Xeon (E5 1400 & 2400 series)	Server	1356	
LGA 3647	2016	Intel Xeon Phi Intel Skylake-SP	Server	3647	
Socket SP3	2017	AMD Epyc Naples AMD Epyc Rome AMD Epyc Milan	Server	4094	

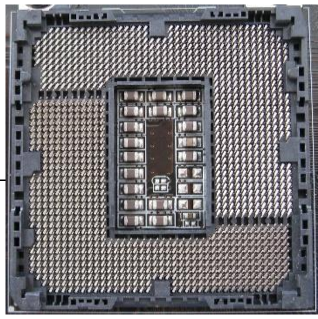
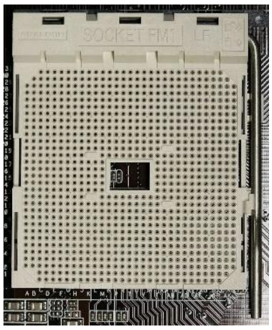
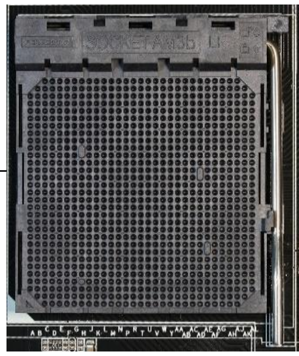
[LGA 2066/](#)	2017	Intel Skylake-X	Server	2066
[Socket R4](#)		Intel Kaby Lake-X		
		Intel Cascade Lake-X		

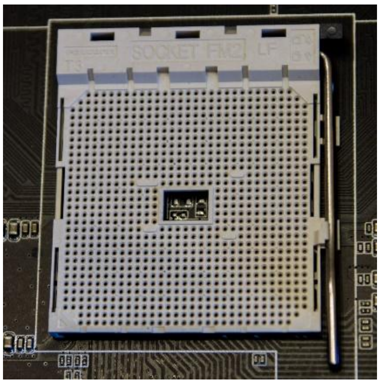
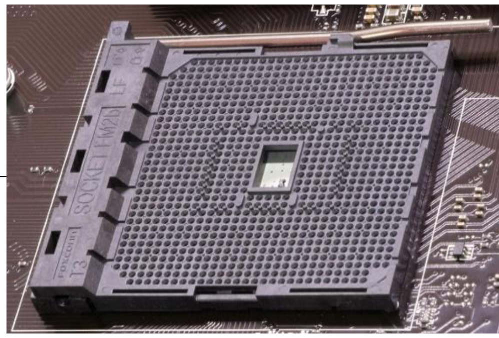
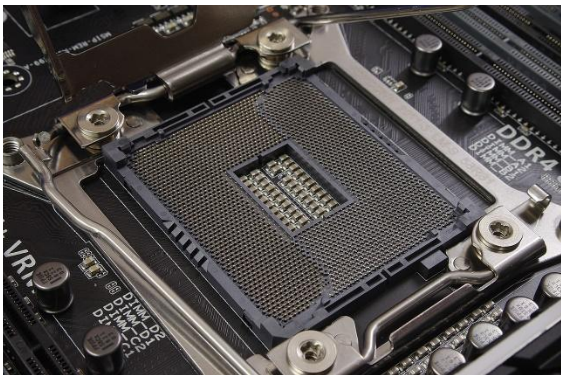
Modern PC Boards: Manufactured from 2003 to the present.
Color: Available in green, brown, red, yellow, or blue.
CPU Slot: Includes a dedicated CPU slot, as detailed in the tables below

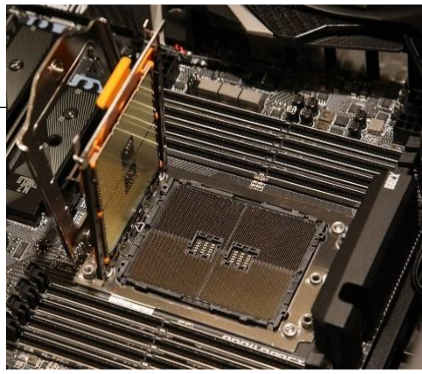
socket name	Year of release	Supported CPU family group	Type of computer	Number of pin	Immage
Socket 754	2003	AMD Athlon 64	Desktop	754	
		AMD Sempron			
		AMD Turion 64			
Socket 940	2003	AMD Opteron	Desktop	940	

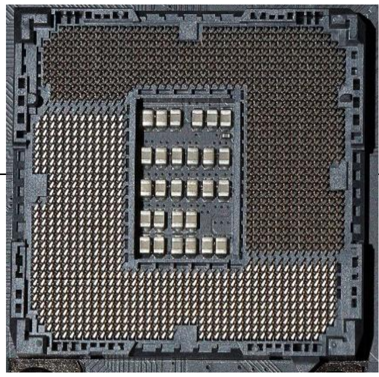
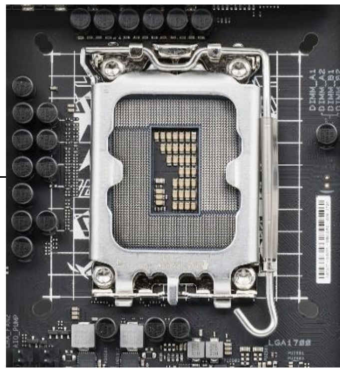
		AMD Athlon 64 FX			
Socket 939	2004	AMD Athlon 64 AMD Athlon 64 FX AMD Athlon 64 X2 AMD Opteron	Desktop	939	
LGA 775/ Socket T	2004	Intel Pentium 4 Intel Pentium D Intel Celeron Intel Celeron D Intel Pentium XE Intel Core 2 Duo Intel Core 2 Quad Intel Xeon	Desktop	775	
Socket AM2	2006	AMD Athlon 64 AMD Athlon 64 X2	Desktop	940	
Socket F/	2006	AMD Athlon 64 FX	Desktop	1207	

Socket L (Socket 1207FX)		AMD Opteron			-
Socket AM2+	2007	AMD Athlon 64 AMD Athlon X2 AMD Phenom AMD Phenom II	Desktop	940	
LGA 1366/ Socket B	2008	Intel Core i7 (900 series) Intel Xeon (35xx, 36xx, 55xx, 56xx series)	Desktop	1366	
Socket AM3	2009	AMD Phenom II AMD Athlon II AMD Sempron AMD Opteron (1300 series)	Desktop	941 o 940	
LGA 1156/ Socket H	2009	Intel Nehalem (1st gen) Intel Westmere	Desktop	1156	

LGA 1155/	2011/Q1	Intel Sandy Bridge (2nd gen)	Desktop	1155	
Socket H2	2011.01.09	Intel Ivy Bridge (3rd gen)			
LGA 2011/	2011/Q3	Intel Core i7 3xxx Sandy Bridge-E	Desktop	2011	
Socket R	2011.11.14	Intel Core i7 4xxx Ivy Bridge-E			
		Intel Xeon E5 2xxx/4xxx (Sandy Bridge EP) (2/4S)			
		Intel Xeon E5-2xxx/4xxx v2 (Ivy Bridge EP) (2/4S)			
Socket FM1	2011	AMD Llano Processors	Desktop	905	
Socket AM3+	2011	AMD FX Vishera	Desktop	942 (CPU 71pin)	
		AMD FX Zambezi			
		AMD Phenom II			
		AMD Athlon II			
		AMD Sempron			

Socket FM2	2012	AMD Trinity Processors	Desktop	904	
LGA 1150/	2013	Intel Haswell (4th gen)	Desktop	1150	
Socket H3		Intel Haswell Refresh			
		Intel Broadwell (5th gen)			
Socket FM2+	2014	AMD Kaveri	Desktop	906	
		AMD Godavari			
LGA 2011-v3	2014	Haswell-E	Desktop	2011	
	(August and September)	Haswell-EP			

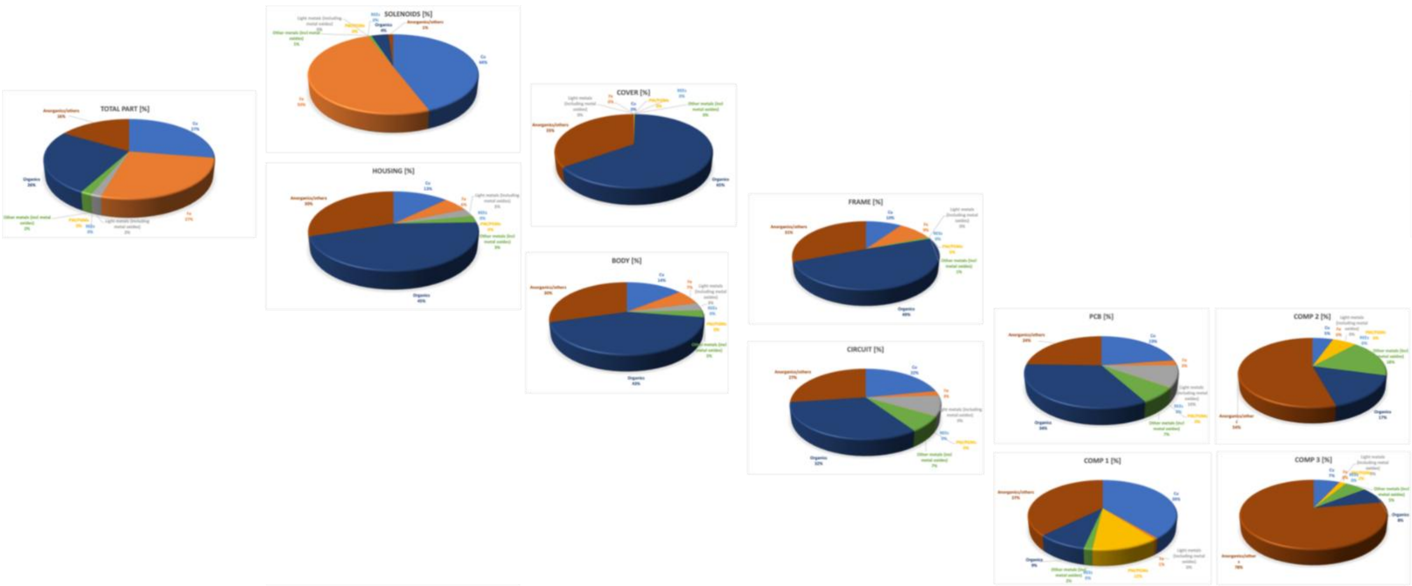
LGA 1151/	2015	Intel Skylake (6th gen)	Desktop	1151	
Socket H4		Intel Kaby Lake (7th gen)			
		Intel Coffee Lake (8th gen)			
		Intel Coffee Lake Refresh (9th gen)			
Socket AM4	2016	AMD Athlon Bristol Ridge	Desktop	1331	
		AMD Athlon Raven Ridge 14nm			
		AMD Athlon Picasso 12nm			
		AMD Ryzen 1000 series			
		AMD Ryzen 2000 series			
		AMD Ryzen 3000 series			
		AMD Ryzen 4000 series			
		AMD Ryzen 5000 series			
Socket TR4/	2017	AMD Ryzen Threadripper (1000 series)	Desktop	4094	

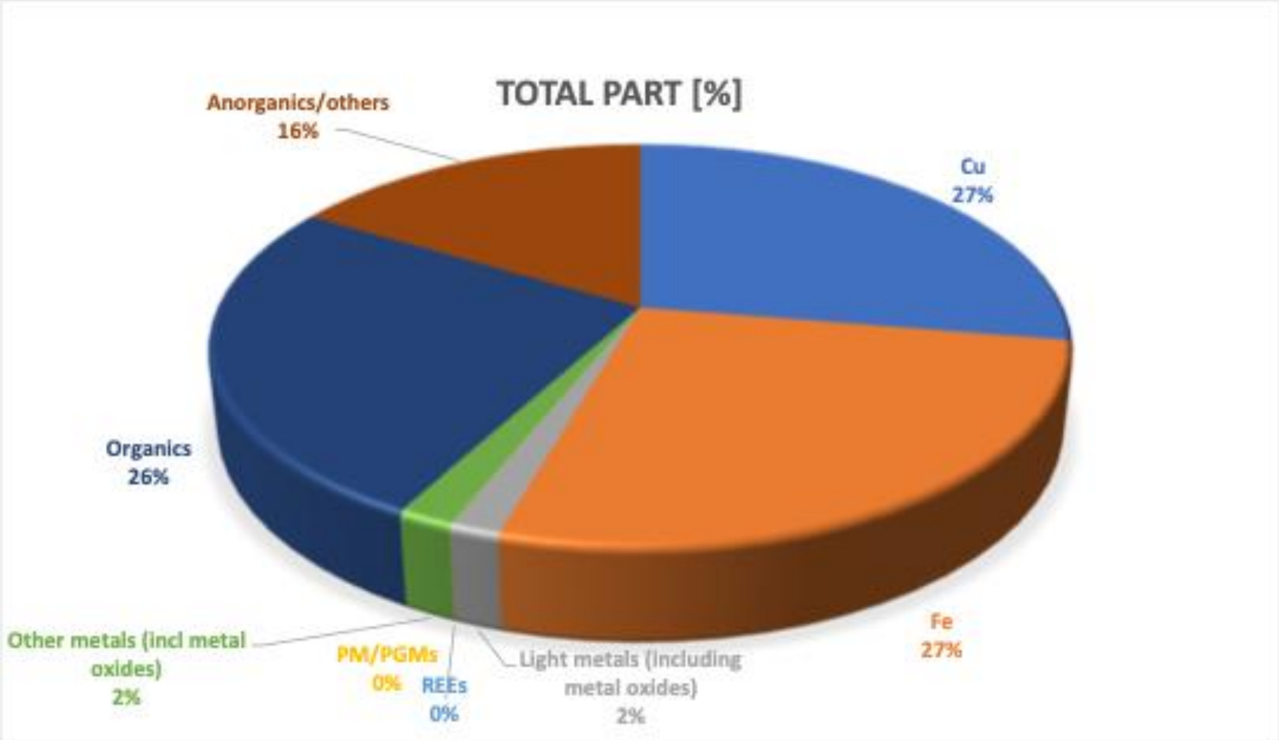
		AMD Ryzen Threadripper (2000 series)			
LGA 2066/ Socket R4	2017	Intel Skylake-X Intel Kaby Lake-X Intel Cascade Lake-X	Desktop	2066	
LGA 1200	2020	Intel Comet Lake (10th gen) Intel Rocket Lake (11th gen)	Desktop	1200	
LGA 1700	2021	Intel Alder Lake (12th gen) Intel Raptor Lake (13th gen) Intel Raptor Lake (14th gen)	Desktop	1700	
Socket AM5	2022	AMD Ryzen 7000 series	Desktop	1718	

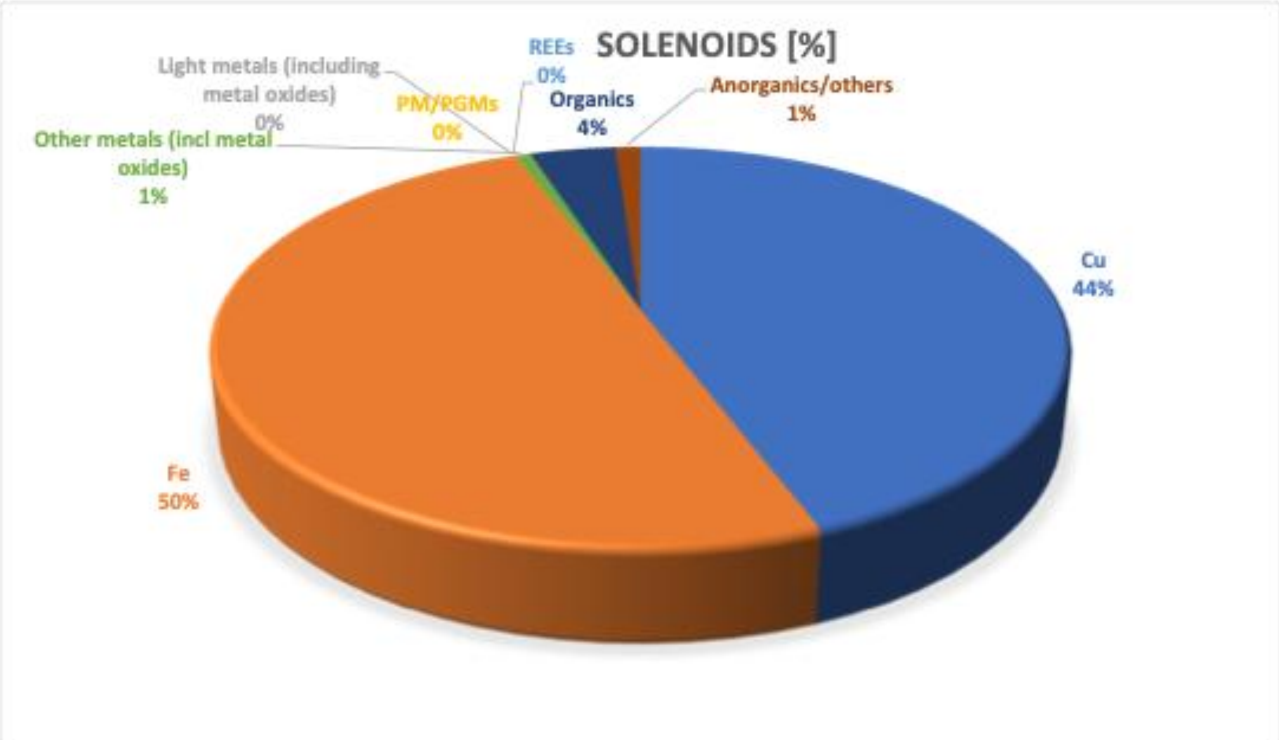
		AMD Ryzen 8000 series (APU)			

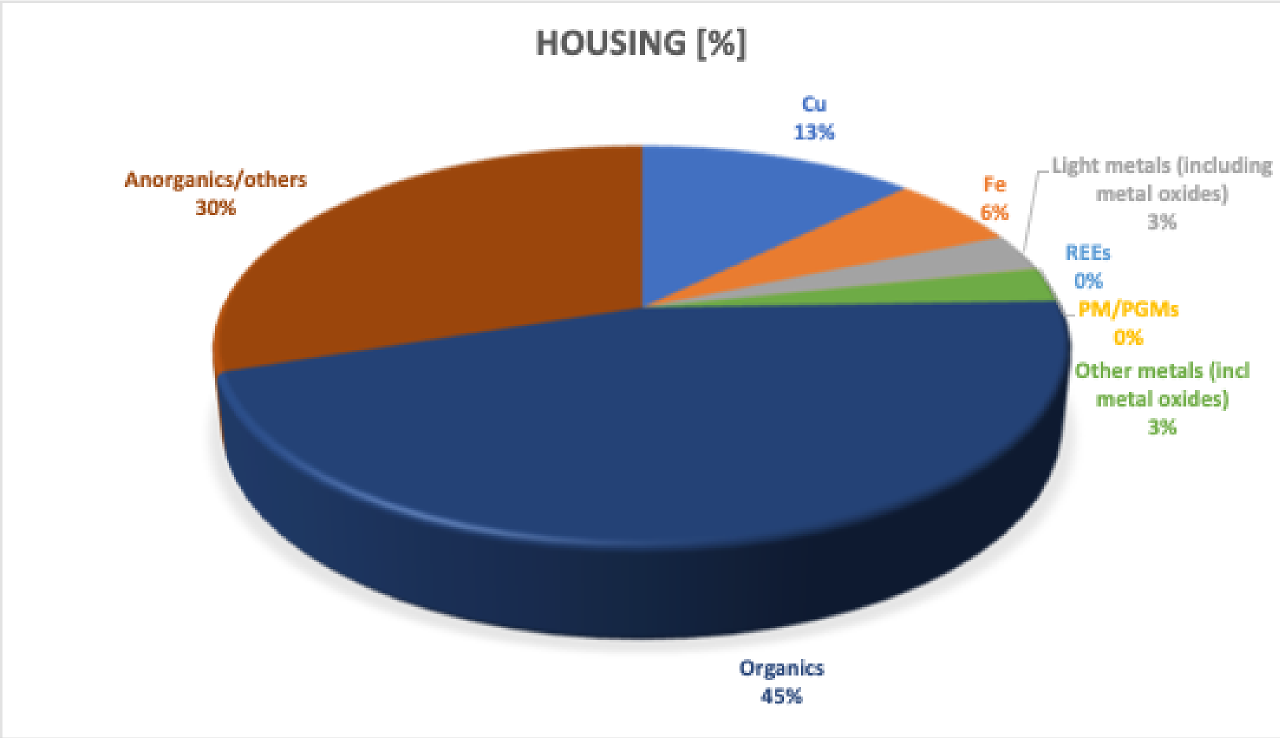
8.4 Annex D

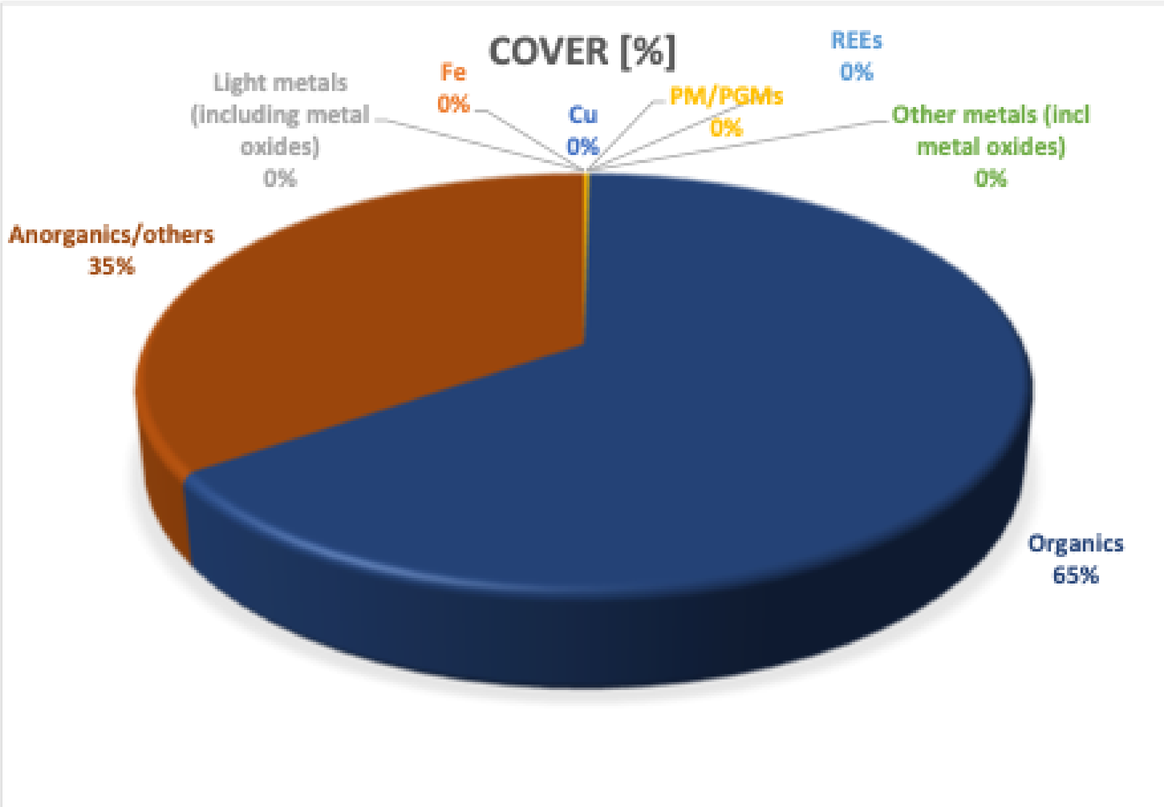
Qualitative recycling analyses & feedback on mass-based assessment linked to compatibility of materials within metallurgical processing infrastructures. *Sub-parts according to the disassembly tree as defined by Bosch.* ***Belonging to figure 44.***

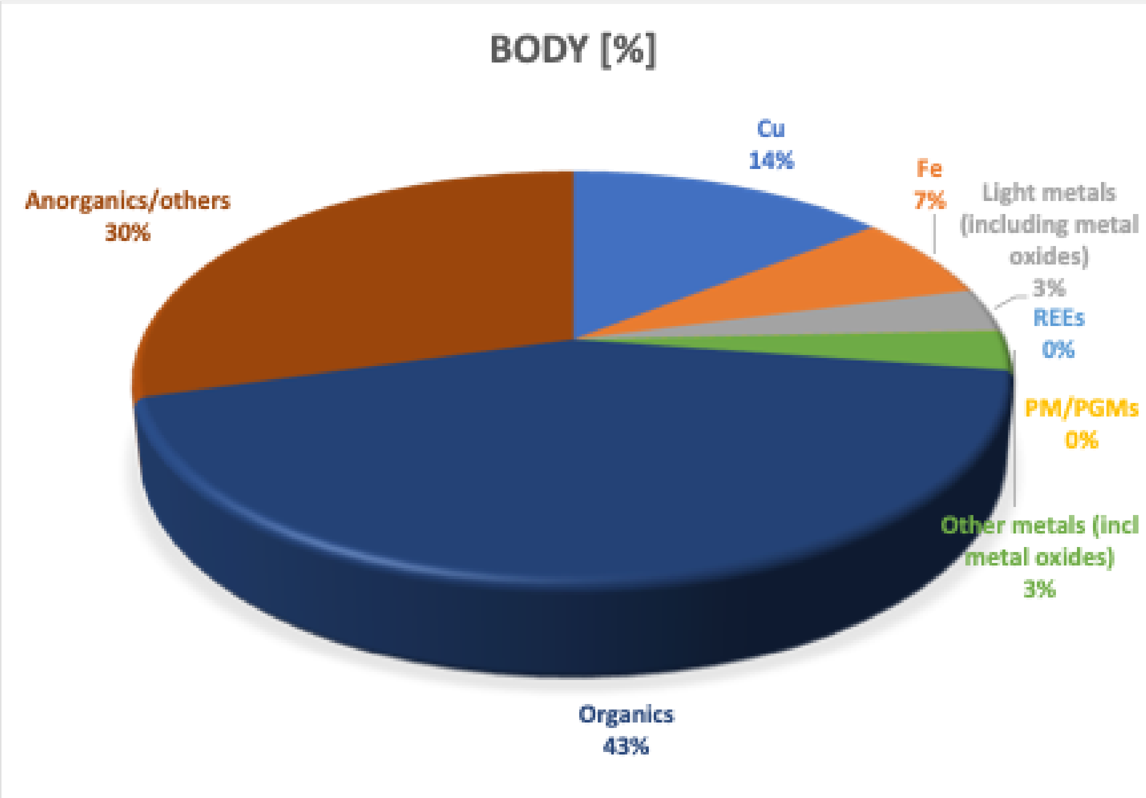


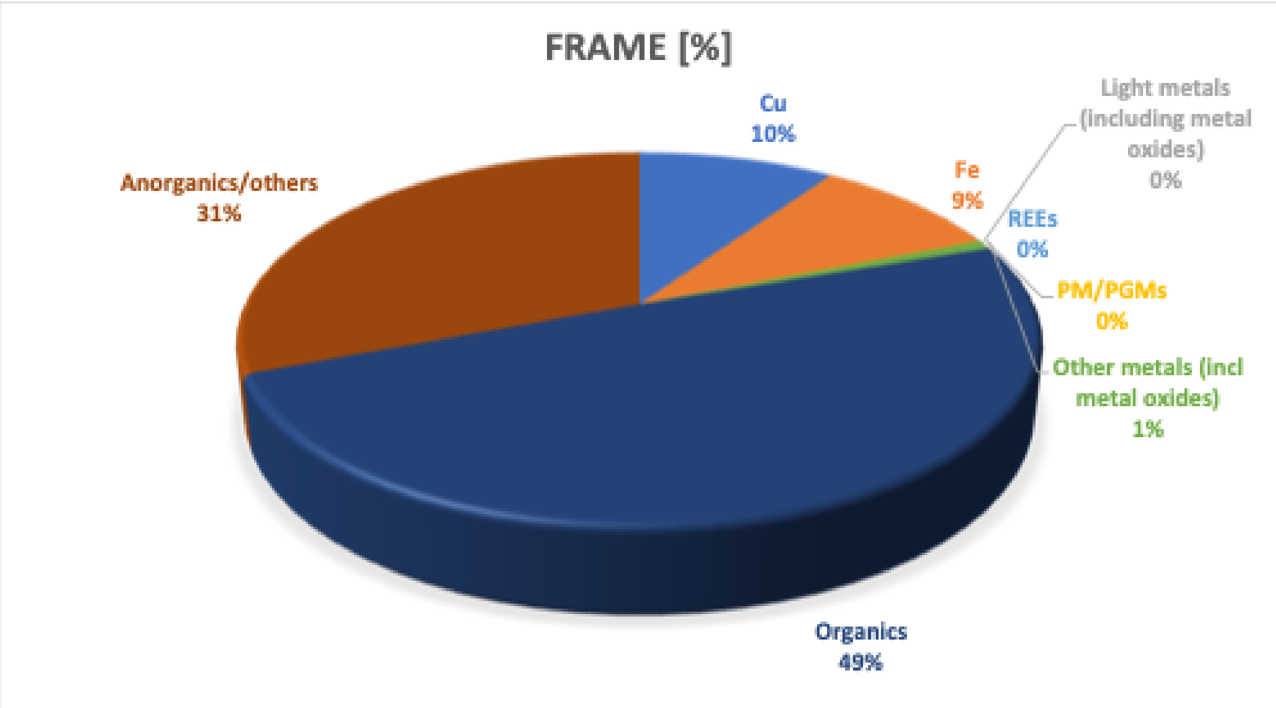

TOTAL PART [%]
Anorganics/others 16%
Cu 27%
Organics 26%
Fe 27%
Other metals (incl metal oxides) 2%
PM/PGMs 0%
REEs 0%
Light metals (including metal oxides) 2%

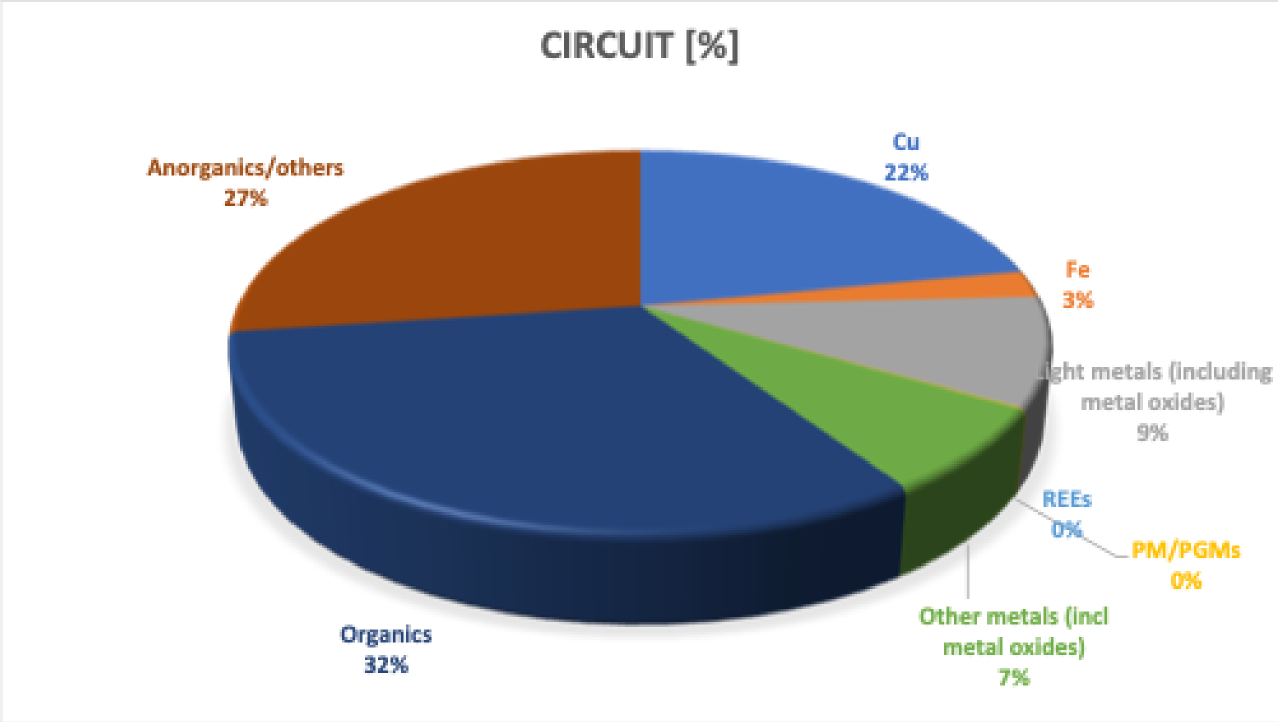

SOLENOIDS [%]
REEs 0%
Light metals (including metal oxides) 0%
PM/PGMs 0%
Organics 4%
Anorganics/others 1%
Other metals (incl metal oxides) 1%
Cu 44%
Fe 50%

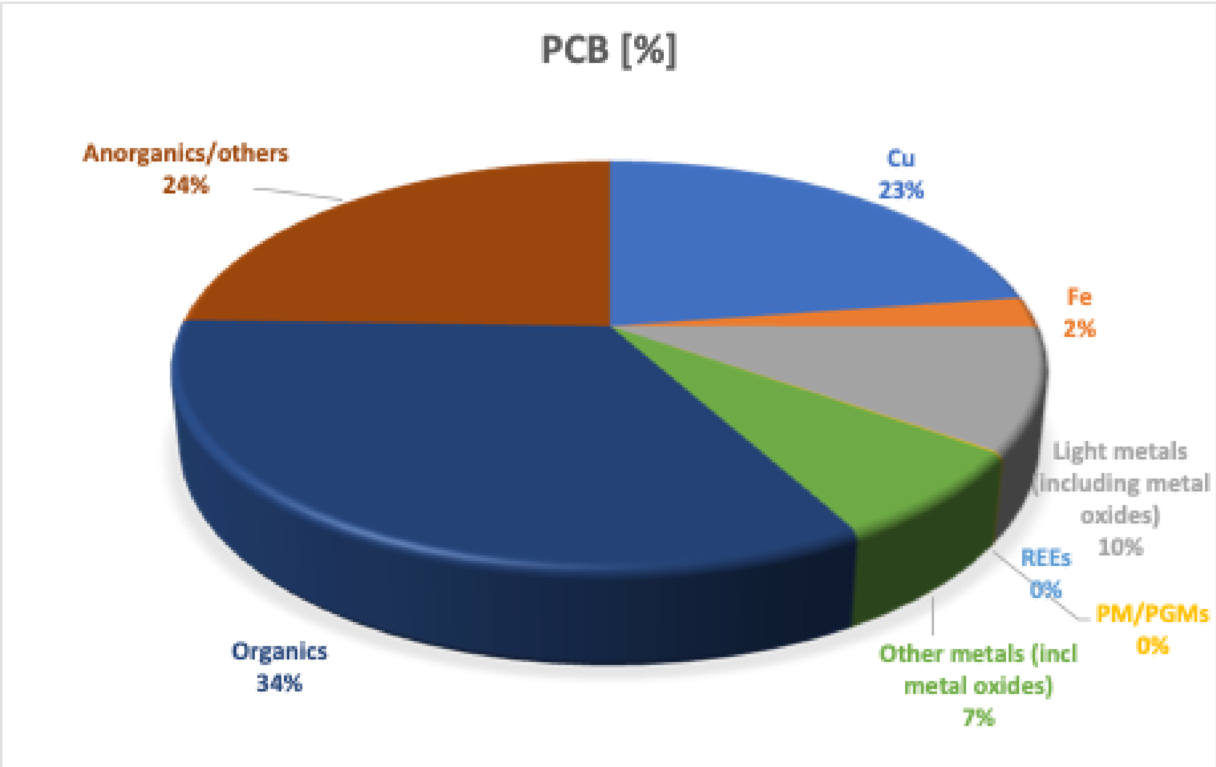

HOUSING [%]
Cu
13%
Fe
6%
Light metals (including metal oxides)
3%
REEs
0%
PM/PGMs
0%
Other metals (incl metal oxides)
3%
Anorganics/others
30%
Organics
45%


COVER [%]
Light metals (including metal oxides)
0%
Fe
0%
Cu
0%
PM/PGMs
0%
REEs
0%
Other metals (incl metal oxides)
0%
Anorganics/others
35%
Organics
65%

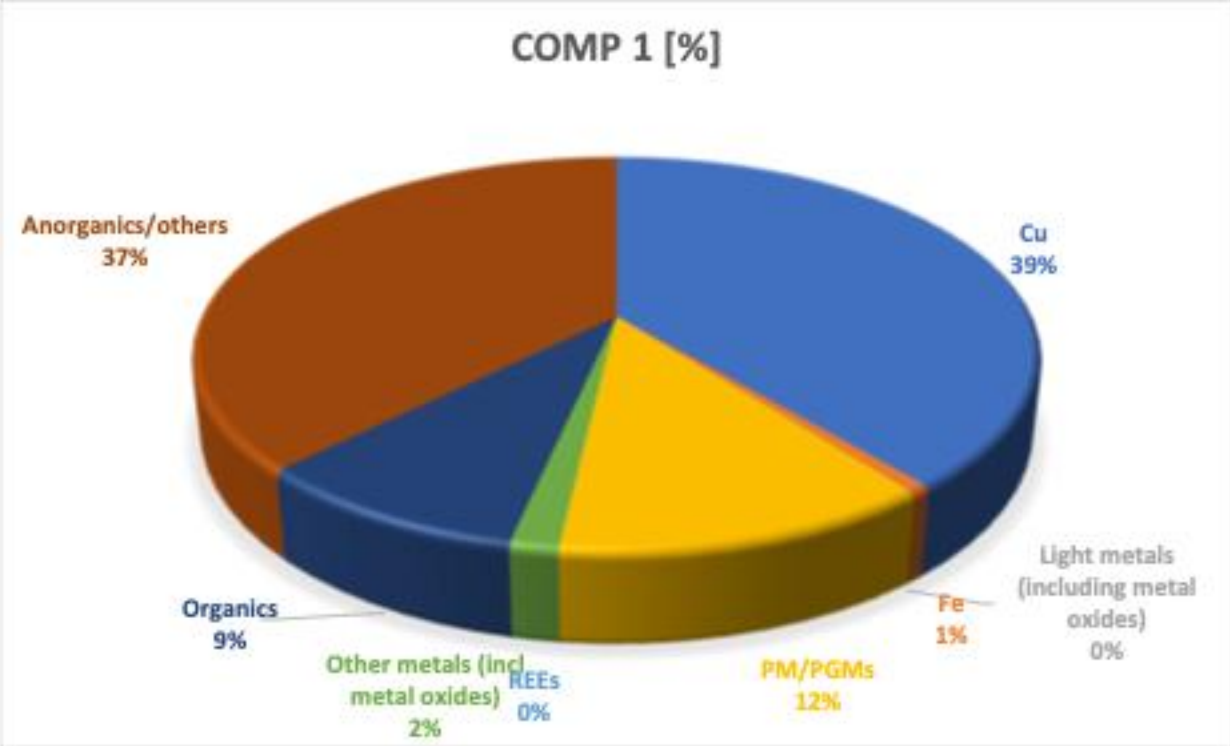

BODY [%]
Cu
14%
Fe
7%
Light metals
(including metal
oxides)
3%
REEs
0%
PM/PGMs
0%
Other metals (incl
metal oxides)
3%
Organics
43%
Anorganics/others
30%

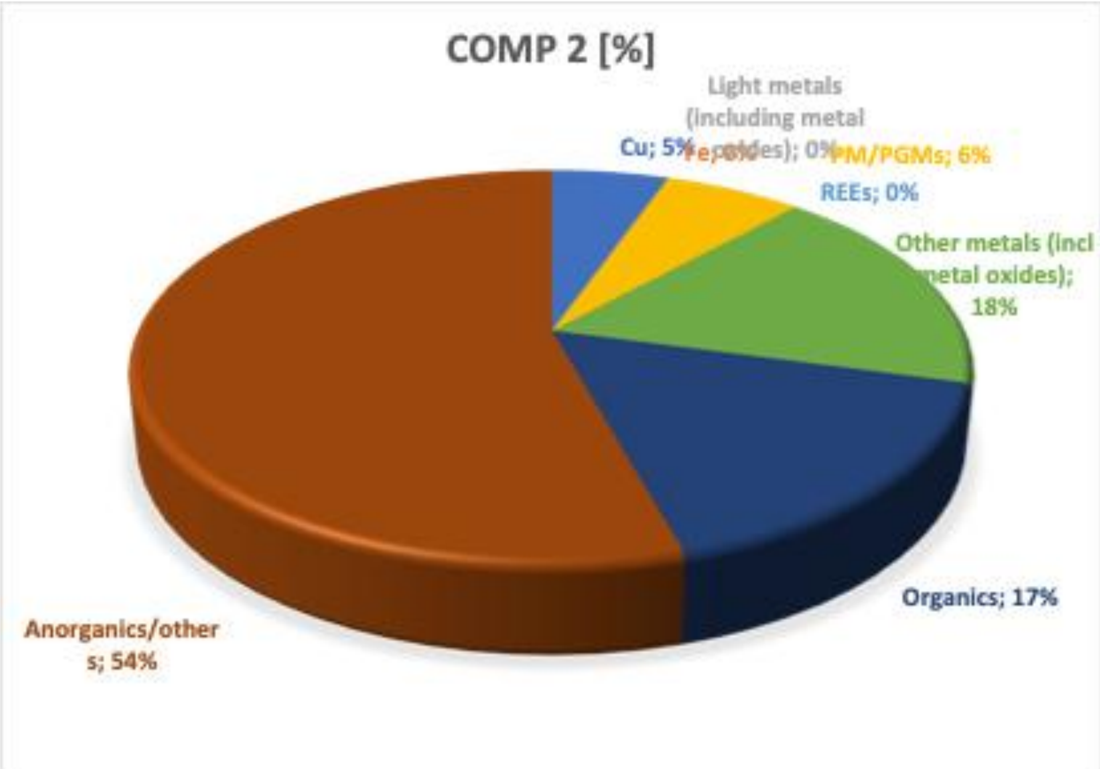

FRAME [%]
Cu
10%
Fe
9%
Light metals
(including metal
oxides)
0%
REEs
0%
PM/PGMs
0%
Other metals (incl
metal oxides)
1%
Organics
49%
Anorganics/others
31%

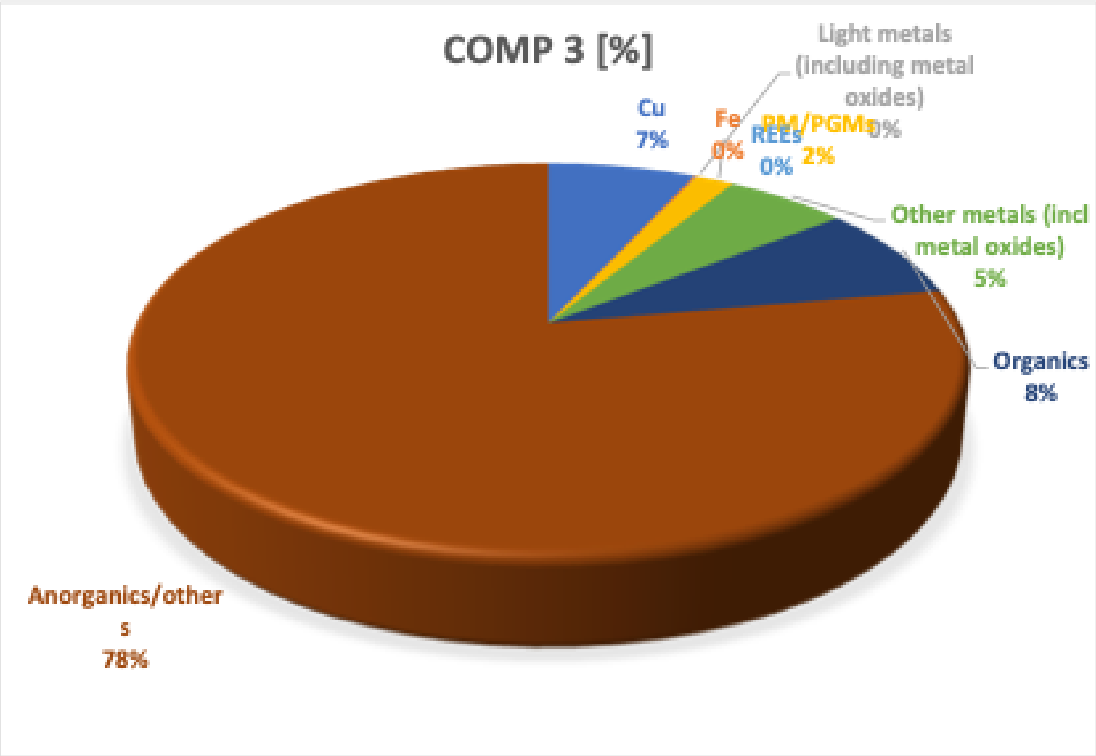

CIRCUIT [%]
Cu
22%
Fe
3%
ght metals (including
metal oxides)
9%
REEs
0%
PM/PGMs
0%
Other metals (incl
metal oxides)
7%
Organics
32%
Anorganics/others
27%


PCB [%]
Cu
23%
Fe
2%
Light metals
(including metal
oxides)
10%
REEs
0%
PM/PGMs
0%
Other metals (incl
metal oxides)
7%
Organics
34%
Anorganics/others
24%

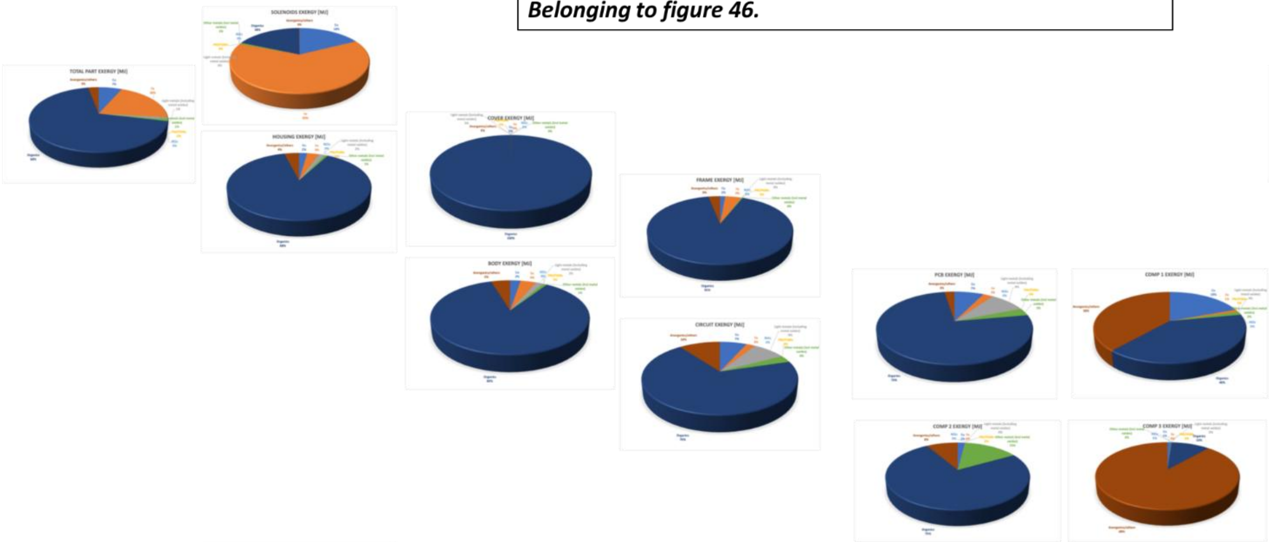
CIRC-UITS

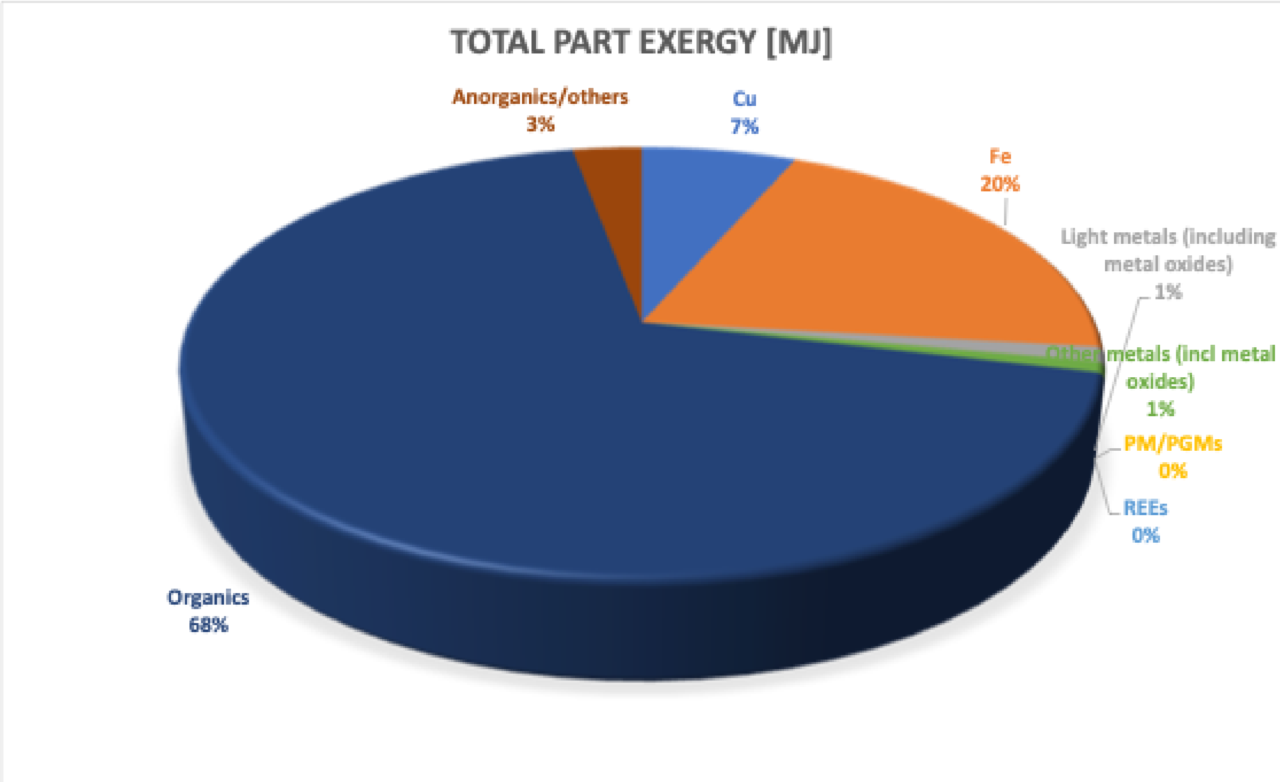

COMP 1 [%]
Anorganics/others 37%
Cu 39%
Light metals (including metal oxides) 0%
Fe 1%
PM/PGMs 12%
REEs 0%
Other metals (incl metal oxides) 2%
Organics 9%

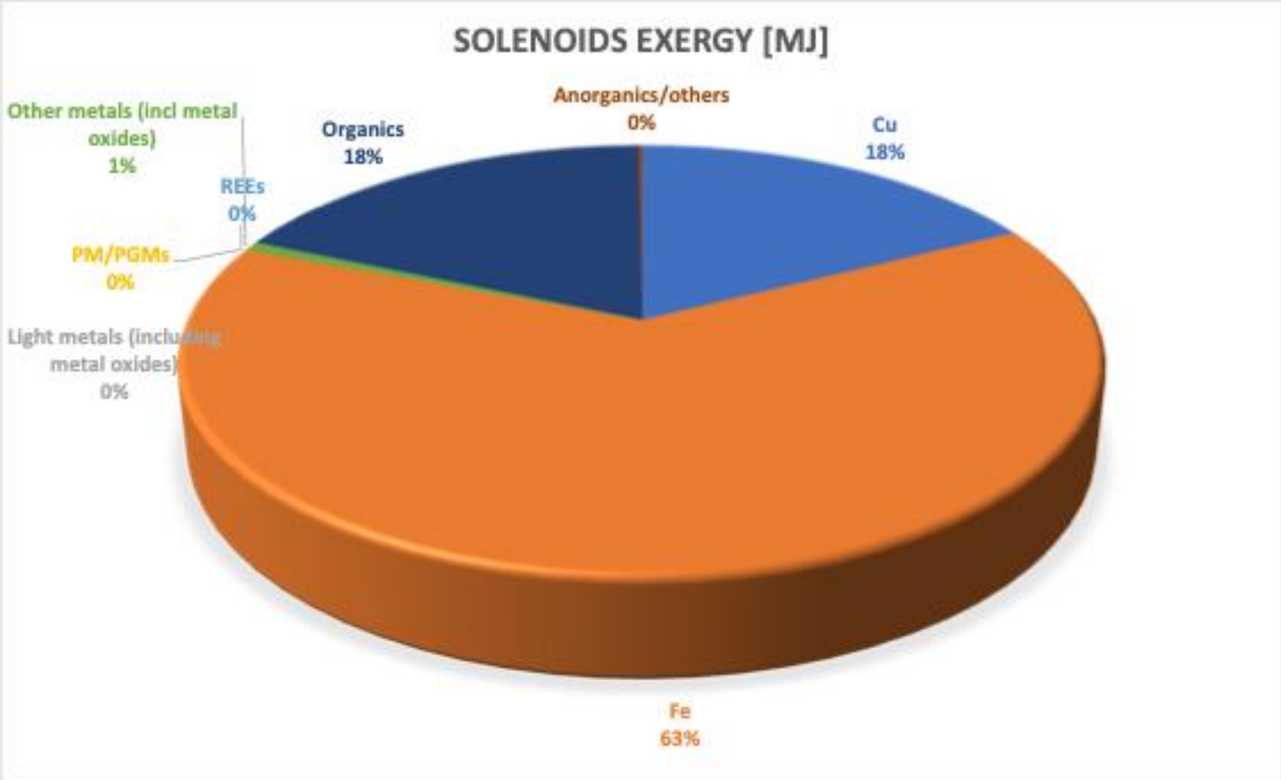

COMP 2 [%]
Light metals (including metal
Cu; 5%
PM/PGMs; 6%
REEs; 0%
Other metals (incl
etal oxides);
18%
Organics; 17%
Anorganics/other s; 54%

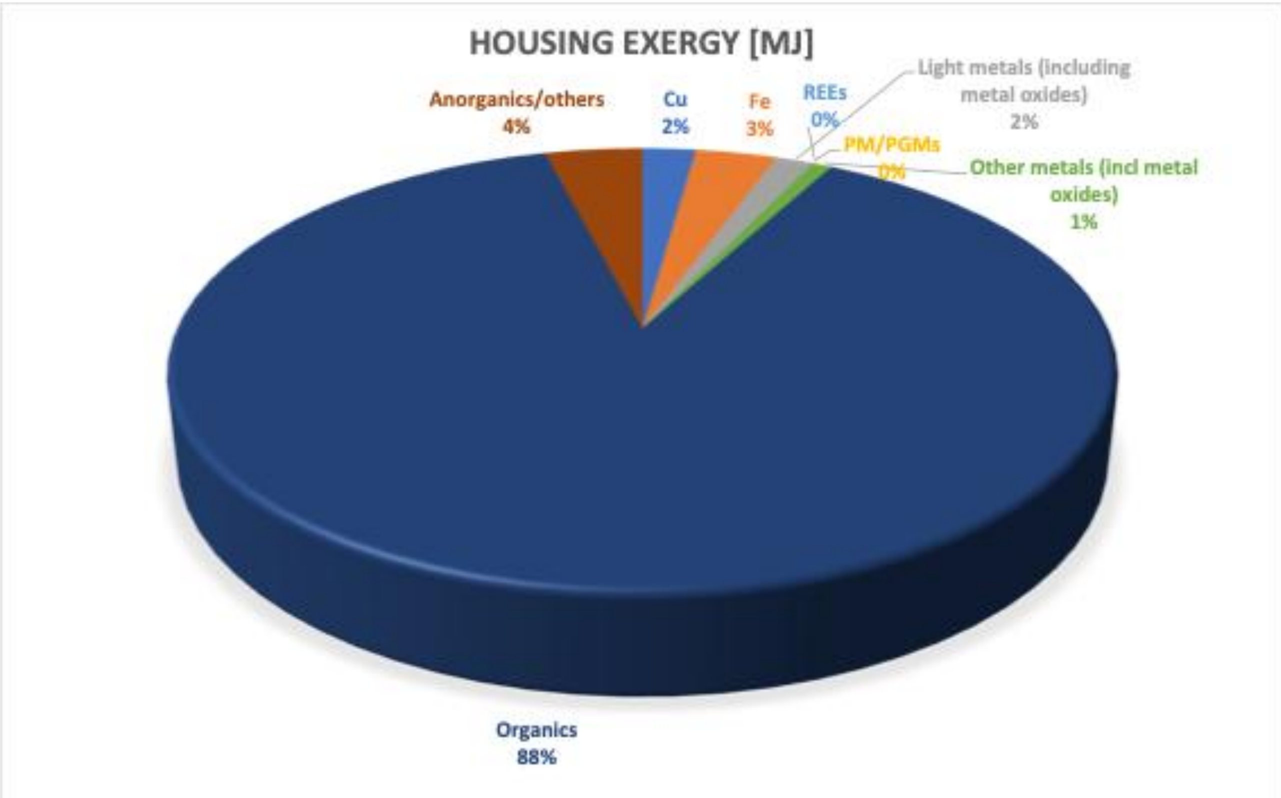

COMP 3 [%]
Light metals (including metal oxides) 0%
Cu 7%
Fe 0%
REEs 0%
PM/PGMs 2%
Other metals (incl metal oxides) 5%
Organics 8%
Anorganics/others 78%

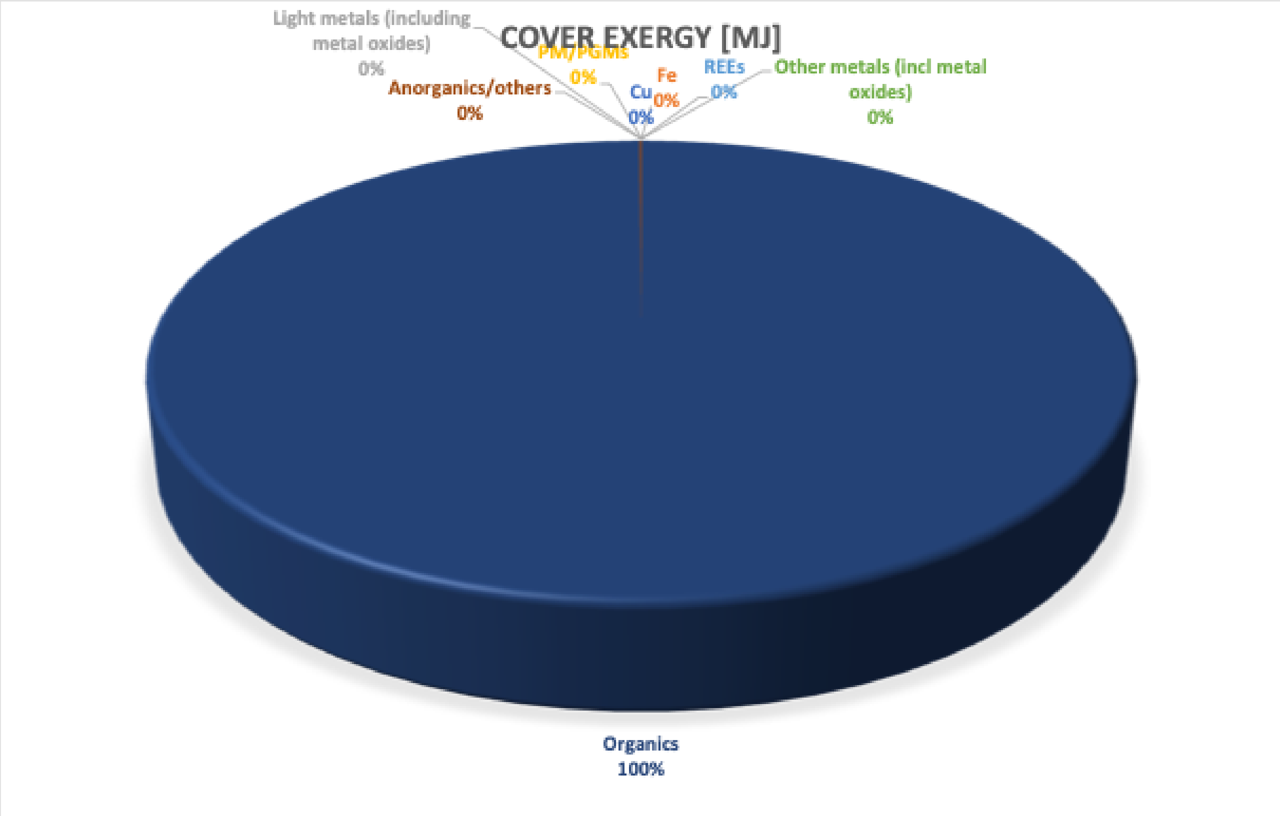
Exergy based assessment of the Bosch ECU and sub-parts according to the disassembly tree as defined by Bosch. ***Belonging to figure 46.***



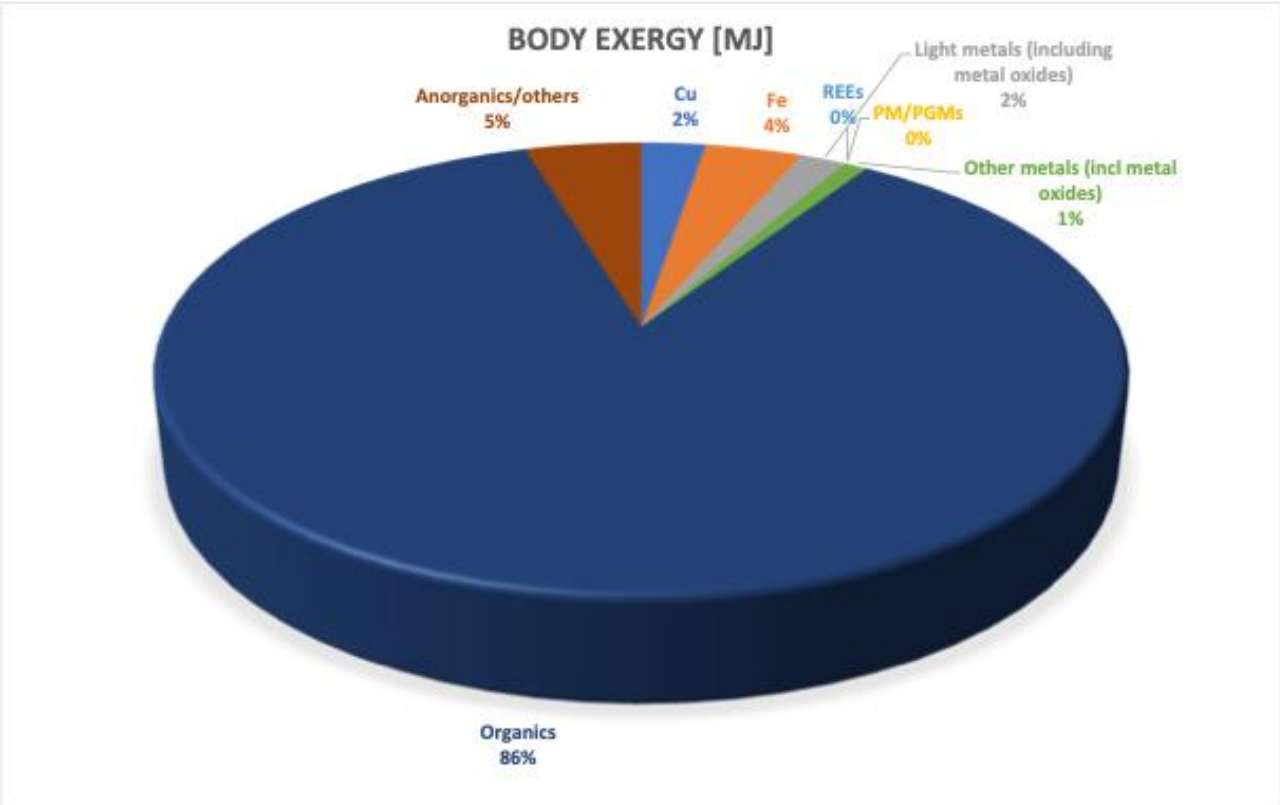



SOLENOIDS EXERGY [MJ]
Anorganics/others 0%
Cu 18%
Organics 18%
Other metals (incl metal oxides) 1%
REEs 0%
PM/PGMs 0%
Light metals (including metal oxides) 0%
Fe 63%

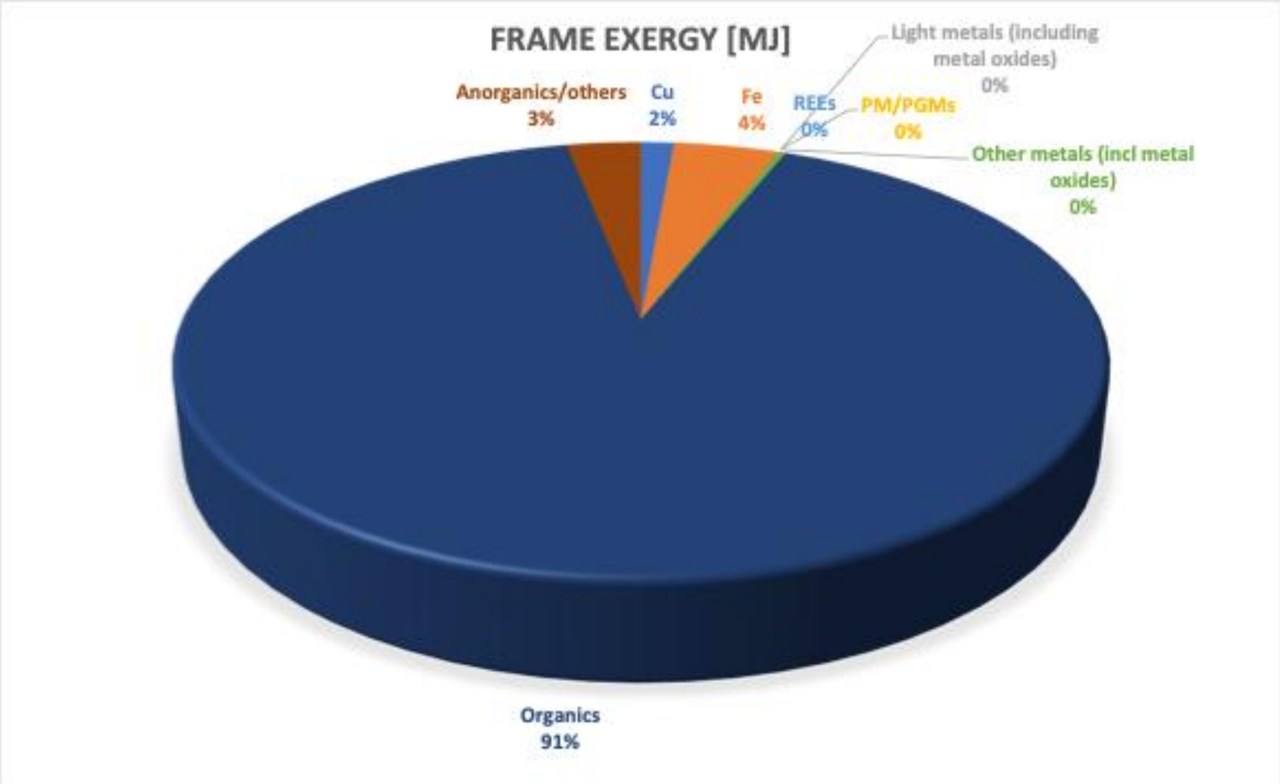

HOUSING EXERGY [MJ]
Anorganics/others 4%
Cu 2%
Fe 3%
REEs 0%
Light metals (including metal oxides) 2%
PM/PGMs 0%
Other metals (incl metal oxides) 1%
Organics 88%

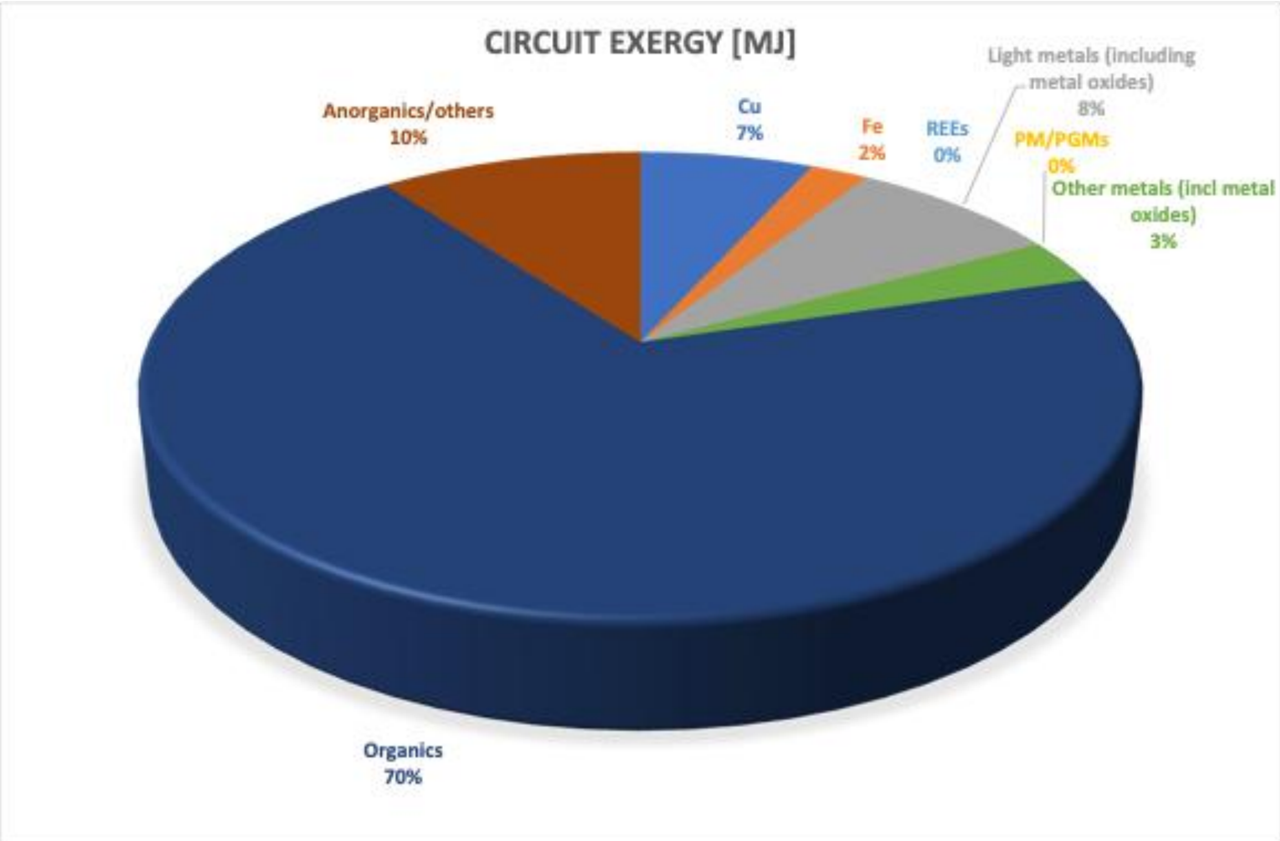


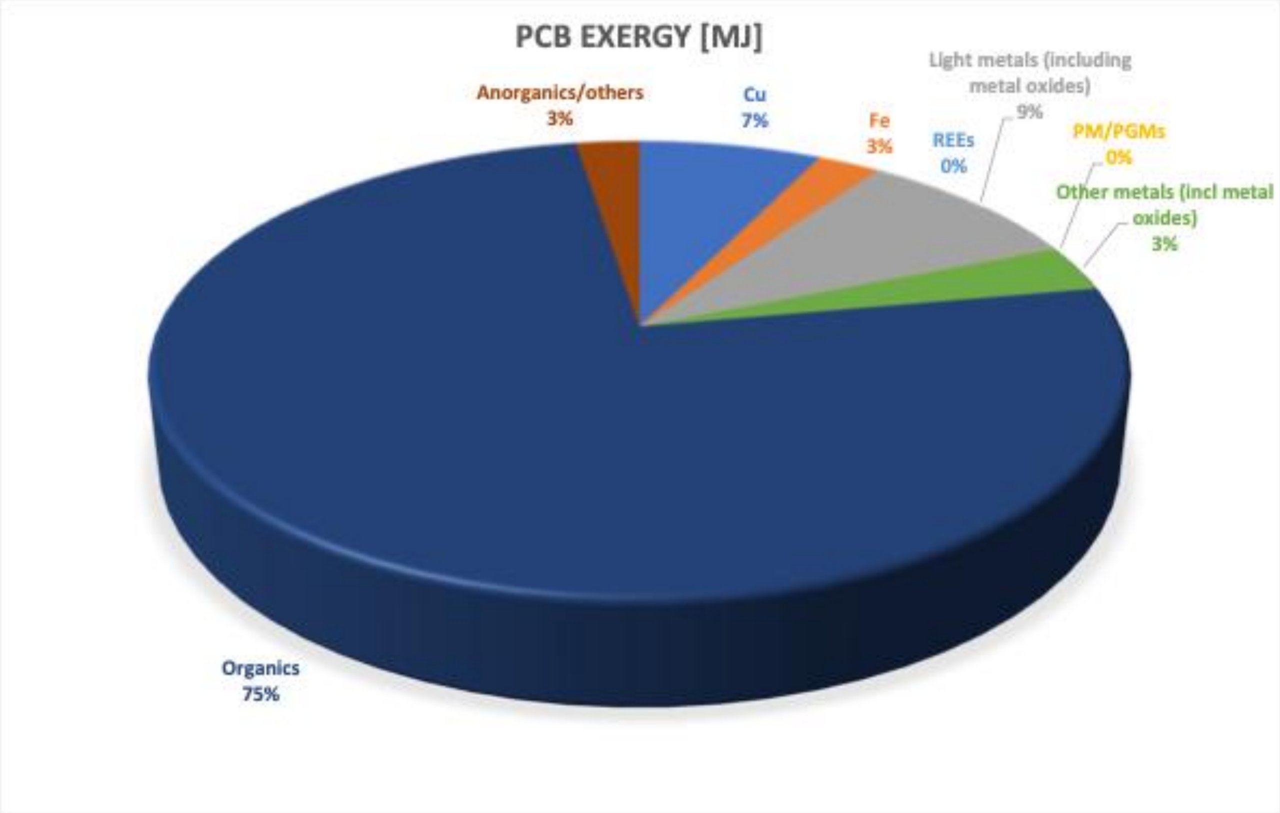
COVER EXERGY [MJ]
Light metals (including metal oxides) 0%
PM/PGMs 0%
Anorganics/others 0%
Cu 0%
Fe 0%
REEs 0%
Other metals (incl metal oxides) 0%
Organics 100%

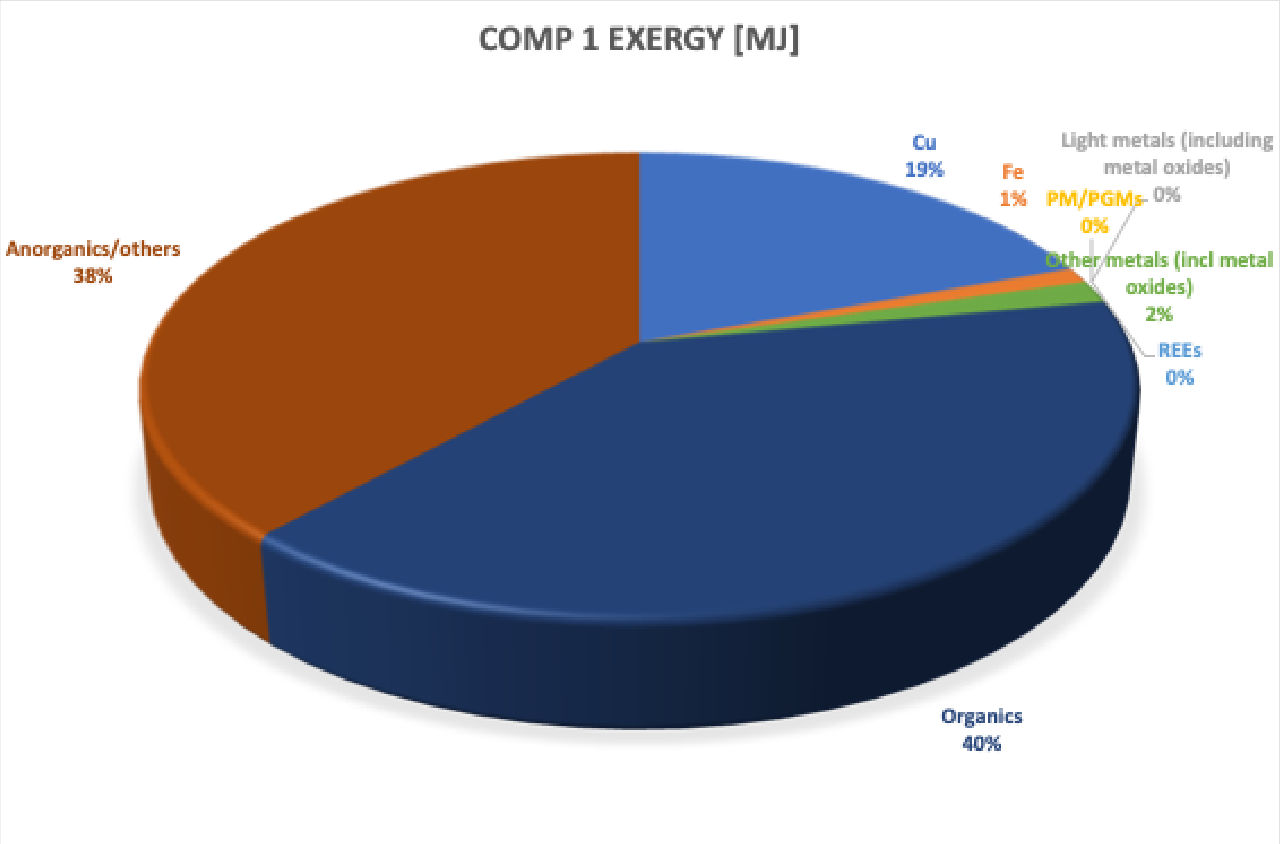


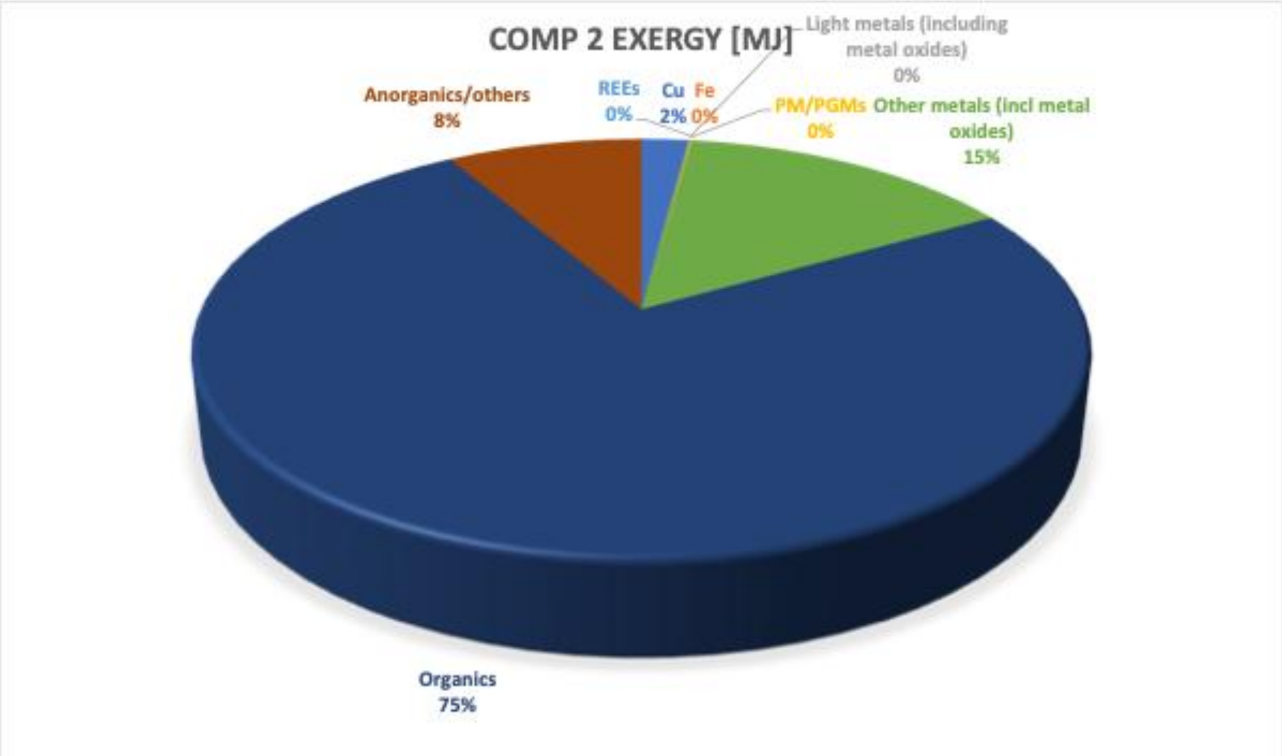
BODY EXERGY [MJ]
Anorganics/others 5%
Cu 2%
Fe 4%
REEs 0%
Light metals (including metal oxides) 2%
PM/PGMs 0%
Other metals (incl metal oxides) 1%
Organics 86%

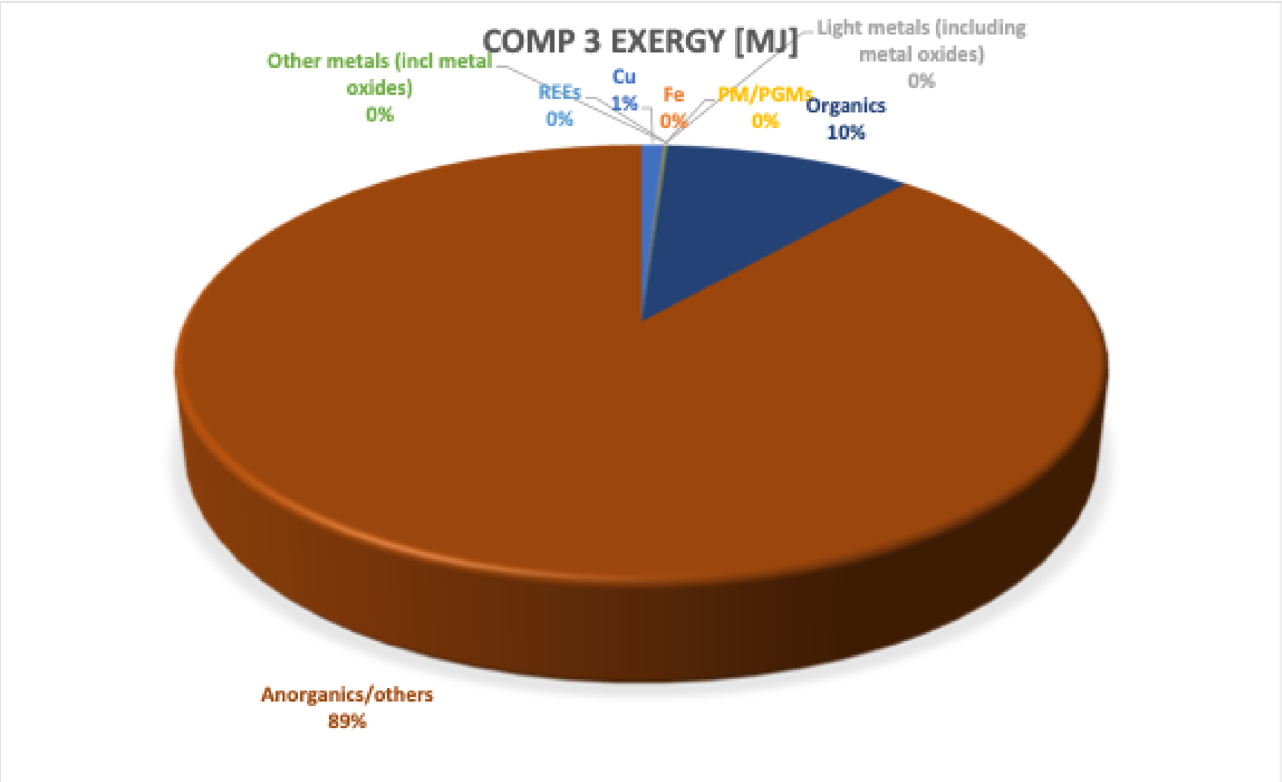

FRAME EXERGY [MJ]
Anorganics/others 3%
Cu 2%
Fe 4%
REEs 0%
Light metals (including metal oxides) 0%
PM/PGMs 0%
Other metals (incl metal oxides) 0%
Organics 91%


CIRCUIT EXERGY [MJ]
Anorganics/others 10%
Cu 7%
Fe 2%
REEs 0%
Light metals (including metal oxides) 8%
PM/PGMs 0%
Other metals (incl metal oxides) 3%
Organics 70%


PCB EXERGY [MJ]
Anorganics/others
3%
Cu
7%
Fe
3%
Light metals (including metal oxides)
9%
REEs
0%
PM/PGMs
0%
Other metals (incl metal oxides)
3%
Organics
75%


COMP 1 EXERGY [MJ]
Cu
19%
Fe
1%
Light metals (including metal oxides)
0%
PM/PGMs
0%
Anorganics/others
38%
Other metals (incl metal oxides)
2%
REEs
0%
Organics
40%


COMP 2 EXERGY [MJ]
Light metals (including metal oxides) 0%
Anorganics/others 8%
REEs 0%
Cu 2%
Fe 0%
PM/PGMs 0%
Other metals (incl metal oxides) 15%
Organics 75%


COMP 3 EXERGY [MJ]
Light metals (including metal oxides) 0%
Other metals (incl metal oxides) 0%
REEs 0%
Cu 1%
Fe 0%
PM/PGMs 0%
Organics 10%
Anorganics/others 89%

Name of the partner The representative of QAT Responsible for business issues **Status:** Approved / Not Approved **Name:** …………………………………………………………………… **Date:** …………………………………………	**Name of the partner** The representative of QAT Responsible for business issues **Status:** Approved / Not Approved **Name:** …………………………………………………………………… **Date:** …………………………………………