D5.6: Simulation of the in-mould / structural electronics prototyping process

07/04/2022 (M11)

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Technical References

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EXECUTIVE SUMMARY

The following topics are discussed in this WP5 deliverable:

- The **current status of the printed electronics pre-pilot** line that is located at TNO
- **Recent results** obtained with the pre-pilot line
- A **simulation of manufacturing** the key-enabling technology – in-mould electronics – with this pre-pilot line
- **Quantification of power consumption**
- Setting up a **lifecycle assessment for in-mould electronics**, to serve as a basis for work together with MARAS using the same tools as will be used for the conventional part in Task 3.3

Task 5.5 examined, tested and simulated the printed electronics pre-pilot line, by manufacturing In-mould electronics (IME) parts. Within the TREASURE project, the IME technology is further improved towards lower environmental impact and, then, applied in a proper demonstrator (to be developed in WP6). The modules of the pre-pilot line were found to function properly. The power consumption is provided in this report. However, data are largely based on equipment specifications, rather than actual measurements (requiring cleanroom modifications – already ongoing). In order to proceed further, a device design is required to match the TREASURE project requirements (e.g. a match with existing convention car part).

An in-mould electronics device has been studied for its environmental impact. While the lifecycle assessment was partially done at the time of writing this report, it is already clear that there are three main contributors (namely polycarbonate, silver and the power consumed during production). PCB and SMDs were not considered yet in this first part of the LCA study. Surprisingly, silver has a remarkably high environmental impact in comparison to polycarbonate, especially when considering their total weights of 0.2 g and 262 g (out of an IME part weighting 294 g). Due to the high impact of silver, terrestrial ecotoxicity and human non-carcinogenic toxicity are almost on par with the global warming potential.

Subsequently, TNO adopted an eco-design procedure for IME parts, adapted to facilitate their disassembly and recycling. Disassembly was accomplished (in this stage of development) by photonic debonding and mechanical dismantling. Photonic debonding allowed the removal of graphic inks from the polycarbonate substrate. The eco-design procedure allowed the removal of the backside filling (e.g. epoxy in this early stage, polycarbonate later on) with a high degree of purity. Mechanical disassembly with the eco-design procedure requires less force, has a specific interface at which the device is split and may be suitable for semi-automated disassembly once further developed. The eco-design procedure further potentially allows circular manufacturing of IME parts, as silver and polycarbonate may be recycled with a high degree of purity. Further experiments are planned to prove this.

All these elements are an integral part of the adjustment of the InScope pre-pilot line to accommodate an IME demonstrator with reduced environmental impact in YR 3 of the TREASURE project.

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1. Introduction

1.1. Project overview

TREASURE – "leading the TRansition of the European Automotive SUpply chain towards a circulaR future" wants to support the transition of the automotive sector towards Circular Economy (CE), by providing a concrete demonstration of how the industry can benefit from the adoption of Circular Economy practices and principles, both from a business and a technological perspective. One of the main encountered issues highlighted by the automotive actors, refers to the huge information gap exigent between Beginning-of-Life (BoL) and End-of-Life (EoL) actors along the whole automotive value chain, up to the final consumers.

TREASURE aims at filling this gap through the development of an AI-based assessment tool that can connect and facilitate the interaction among the key involved stakeholders dedicated to car electronics: car parts suppliers, car makers, dismantlers, and shredders. On the other hand, TREASURE aims at assisting both BoL and EoL actors in performing their operations (e.g., car parts design, disassembly, dismantling operations), taking the most suitable decision according to up-to-date information, as well as in assessing the impact and the effect of their decision on the final customers.

To this aim, a web-based platform will be developed as a new information sharing tool among all stakeholders, both in forward and backward directions, ensuring secure access and confidentiality. The platform will indeed be developed in order to enhance the connection among the actors, making information available through specific modules that will be built and tailored according to their needs.

The platform will be tested with a set of dedicated demonstration actions within the project boundaries. However, it will be designed assuring that its potential can go beyond the project and its sustainability will be properly defined and agreed with the TREASURE consortium, guaranteeing the possibility for its scale-up and adoption by a wider group of stakeholders.

1.2. Scope of the deliverable

In the third defined demonstration action, "*assessing in-mould/structural electronics circularity level in the automotive sector*", "*the challenge is to assess how printed electronics components can be exploited for new automotive applications in a sustainable strategy, and to determine how embedding electronics into 3D formable parts will impact the circularity performance of the automotive sector."*

It is further defined in the TREASURE proposal (SEP-210687536) that "*TNO will assess how flexible electronics can be exploited in the automotive sector to serve sustainability goals. TNO will also consider the recyclability of future automobile components consisting of embedding electronics directly into 3D forms and the implications for recovery and reuse. WALTER, SEAT and MARAS will assist TNO in identifying the best options for adopting new flexible electronic components and applied processes for production. Prototypes will be created to demonstrate the identified technology for sustainability. UNIVAQ will validate the recycling of flexible printed electronics from practical point of view, whereas MARAS will apply recycling system modelling of the production of carrier and precious metals as well as (non)organics from the flexible electronics as a function of construction, material applications and connections as well as disassembly possibilities.*"

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The TREASURE document SEP-210687536 mentions for Task 5.5:

- Based on the knowledge gained from benchmarking conventional to structural electronics the (optimised) process for prototyping will be developed.
- Simulation of the consecutive steps in the process with material and energy consumption will quantify anticipated results.

This deliverable fulfils the description for Task 5.5 by proving descriptions of

- The **current status of the printed electronics pre-pilot** line that is located at TNO
- **Recent results** obtained with the pre-pilot line
- A **simulation of manufacturing** the key-enabling technology – in-mould electronics – with this pre-pilot line
- **Quantification of power consumption**
- Setting up a **lifecycle assessment for in-mould electronics**, to serve as a basis for work together with MARAS using the same tools as will be used for the conventional part in Task 3.3

In addition, improvements to the KET, especially targeting the improvement to environmental impact of the technology by improving recyclability of the technology, were described in the TREASURE proposal, however for Task 5.6. This report summarizes the first step to determine what to improve, namely a lifecycle assessment (LCA), followed by experiments that could indeed improve recyclability. Execution of these tasks ahead of schedule favours proper execution of Task 5.6 and to better intertwine the studies in WP3 on the conventional car parts, overlap with LCA developments in WP3 and WP4, and possible adaptations to the tools developed in WP2. Moreover, the outcomes of Task 5.5 and Task 5.6 will benefit activities in WP6.

1.3. Links to other WPs

As stated in section 1.2, the work described in WP5, task 5.5, has several links to the other work packages:

For WP3 activities, WP5 partners have participated to discuss dismantling of conventional and printed electronics, and interacted with all TREASURE partners to come to the best selection of conventional car parts to allow a direct and accurate comparison of both types of technologies in future TREASURE activities (e.g. LCA, demonstration purposes). WP3 serves as input for possible car electronic modules to realize as IME part. This may for instance be a climate control unit.

For WP4 activities, WP5 partners have participated in all workshops and provided input where needed for the accurate comparison of conventional electronics to printed electronics and specific details of dismantling and recycling in-mould electronics. This should enable a better integration of future car electronics based on IME in the three modules designed for the TREASURE platform. WP5 activities are further connected to WP4 activities in the sense that WP5 partners have begun a LCA analysis on IME with available software tools and existing methodologies. In Task 5.5, we followed the currently accepted methodology to base material data, transportation data, recycling and other end-of-life (EOL) scenarios on generalized data that lead to a flawed and incomplete evaluation of LCA and EOL. Through this exercise, a direct comparison between generalized and state-of-the-art methodologies by Maras is possible within the TREASURE project. This topic is not completed before M12 and will require more time.

Current activities keep in mind the planned WP6 activities on validation and demonstration, wherein the following points are addressed

1. An in-mould/structural electronics prototyping process will be implemented @ TNO's Holst Centre based on the improved technology for recyclability from WP3
2. Researchers will be trained on green printed electronics production processes and materials. In addition, they will have the chance to compare green in-mould/structural electronics production process performances with current ones in terms of circularity levels, by exploiting TREASURE platform's potentialities
3. Modelling will be applied to quantify the gain in the improved structural electronics (see T4.5)

To some degree, we are preparing or are working on these topics to allow proper execution of these tasks.

For WP7, we are following recommended and agreed upon dissemination actions and participate in large conferences to disseminate our objectives and successes.

2. In-Mould Electronics

2.1. IME introduction

In-mould electronics (IME) is one of the approaches to 3D electronics, alongside (e.g. 3D printed electronics and functional film bonding), in which electronics are integrated into an object with a 2½ or 3D-shape. It combines known production methods called In-Mould Decoration or In-Mould Labelling with an alternative approach to electronics, namely by printing wires and circuitry, and bonding SMD components onto the printed circuitry. By printing or adding SMD components, IME provides a great deal of added functionalities (e.g. light source, sensors, actuators). Unique to IME is the combination of printed electronics onto 2D substrates and high-pressure thermoforming in order to achieve the 2½ or 3D shape. Subsequent injection moulding provides stability, rigidity and encapsulation of printed electronics from environmental influences. Key benefits of IME over conventional electronics include space/weight reduction, free-form designs, simpler assembly and reduced dependency of PCBs. Challenges include costs, yield, inability to achieve all 3D designs, reliability (in comparison to mature PCB technology), increased complexity of design when attempting to replace the entire PCB. Since the electronics is fully encapsulated into plastic, recycling/re-use is not necessarily easier compared to PCBs.

IME is suitable for smart surfaces (human-machine-interfaces) in various domains, for instance automotive, consumer electronics, aviation and healthcare. The technology is still in development and has not reached full market acceptance.

2.2. IME device build-up

Different manufacturing routes may be used to realize similar IME parts. Roughly summarized, there are three main approaches: 1) single-foil approach, 2) two-foil approach, 3) functional film bonding. The latter approach does not embed the electronics within the in-moulded part and is limited in terms of functionalities, since SMD components appear not to be compatible with the described method of bonding the sensor foil to the injection moulded front part (by lamination).

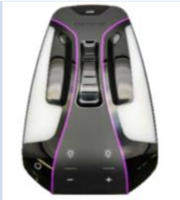
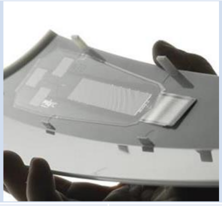
	Holst Centre		Tactotek		Kurz	
						
Approach	**1-foil**	All-in-one	**2-foil**	Separate processing	**2-foil**	FFB
Sequence	PR, TF	IJM	2xPR, (2x)TF	(2x)IJM	PR, TF	IJM, LAM
Functionalities	Embedded, *frontside* foil		Embedded, *backside* foil		Backside laminated	
Details					No SMD components, only (intended for) printed sensor foils	

Figure 1: three approaches to create IME (or similar)

TNO focuses on the single-foil approach, wherein the flat polycarbonate substrate is covered by both graphics and electronics. In the two-foil approach, the graphics and electronics are applied to the frontside and backside foil, respectively. Tactotek is a well-known Finnish SME (spin-off from VTT) for their pioneering work on In-Mould Electronics. Tactotek is not pursuing mass manufacturing of IME, but instead licenses their IP to Tier 2 or Tier 1 automotive suppliers, or generalized IME manufacturing companies. Since both methods are rather similar, manufactures may select one or the other approach to realize a functional IME part.

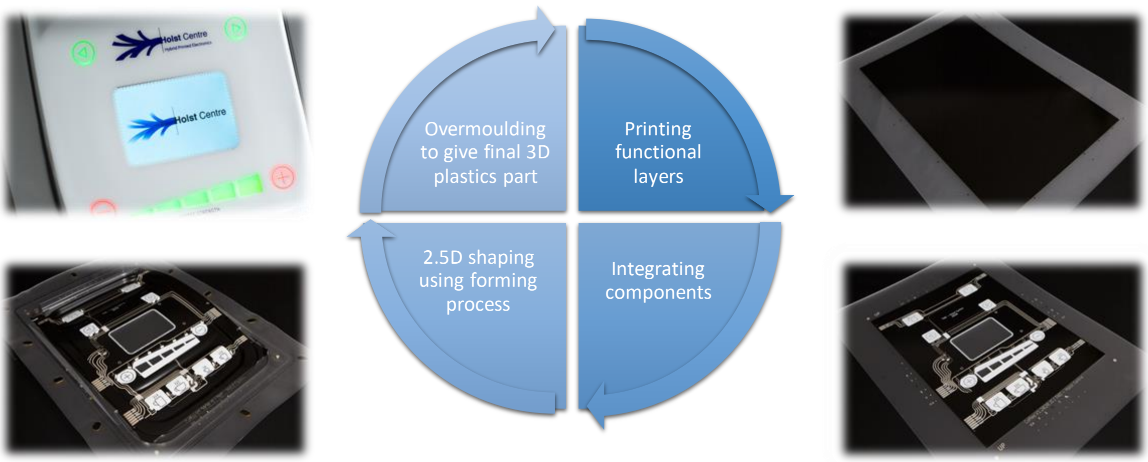


Figure 2: rough process flow for single-foil IME-based coffee machine interface panel

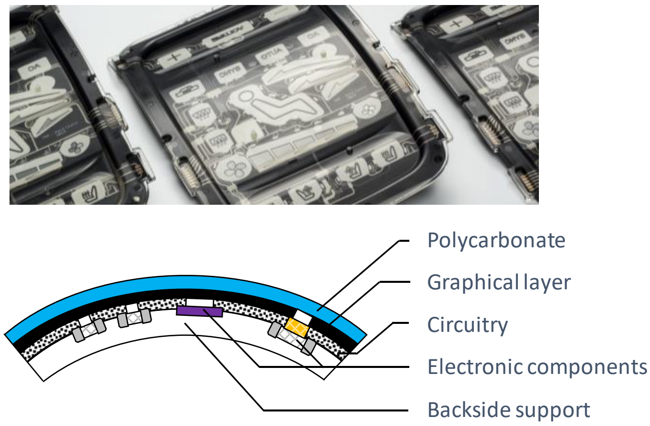


Figure 3: layer stacking for single-foil IME

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It should be noted that Figure 2 intentionally shows a coffee machine panel, rather than an interface panel for a car's dashboard or mid-console. The reason is that, although an automotive panel has been made at TNO (as shown in Figure 3), the coffee machine panel more accurately represents a console for automotive purposes, due to the combination of embedded functionalities. Since dashboard and mid-console elements usually contain displays, an IME panel for the same purpose should be able to feature the same. Since within TREASURE an IME device is compared to a panel based on conventional electronics, the environmental impact of an IME device with a display should be considered. For this reason, the remainder of the activities in this document (process flow description, LCA) focuses on the coffee machine panel.

2.3. IME part manufacturing process

2.3.1. Default sheet-to-sheet manufacturing process for IME

At TNO, IME devices are typically produced using a sheet-to-sheet process. The process flow for an IME prototype created by a S2S process by Holst Centre (TNO) is provided below. Onto a flat polycarbonate substrate of 390x260 mm^2, various layers of graphics were separately printed and hereafter cured. On top the graphic layers, the circuitry was printed with alternating Ag, dielectric and Ag. The circuitry enables capacitive touch functionality and operation of the programmable RGB LED lighting. Following thermoforming at high temperature and pressure, injection moulding with polycarbonate resin was performed by a third party to complete the part. In a final lamination step, the LCD display was added to the coffee machine panel. Assembly into a commercial household appliance was achieved by inserting the IME part into a 3D printed element that was mounted onto the appliance's interface. Additional PCB boards were required for operation of the IME panel and the display. The coffee machine panel features 10 capacitive buttons, 1 capacitive slider consisting of 5 segments, and further contains 73 SMD components (LEDs, resistors, capacitors, capacitive driving chips). It consumes roughly 3.8 W in operation, including PCBs, but without the coffee machine itself.

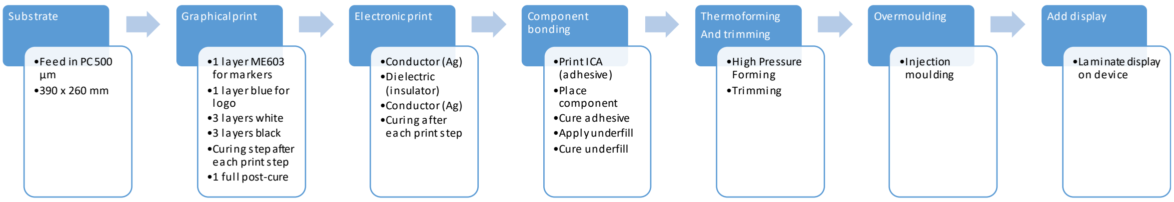

Figure 4: process flow for single-foil IME

2.3.2. Simulation of roll-to-roll IME manufacturing using the InScope pre-pilot line

Essential to the manufacturing of IME parts within the TREASURE consortium is the simulation of the roll-to-roll process using the InScope flexible electronics pre-pilot line. Roll-to-roll production of IME parts requires an adjusted way of working and is more complex in its implementation due to 1) web handling, 2) curing of the devices in a roll-to-roll fashion, 3) higher speed pick & place deposition of SMD components and subsequent bonding and underfilling (additional gluing step for the SMD components), 4) cutting to size and 5) inspection.

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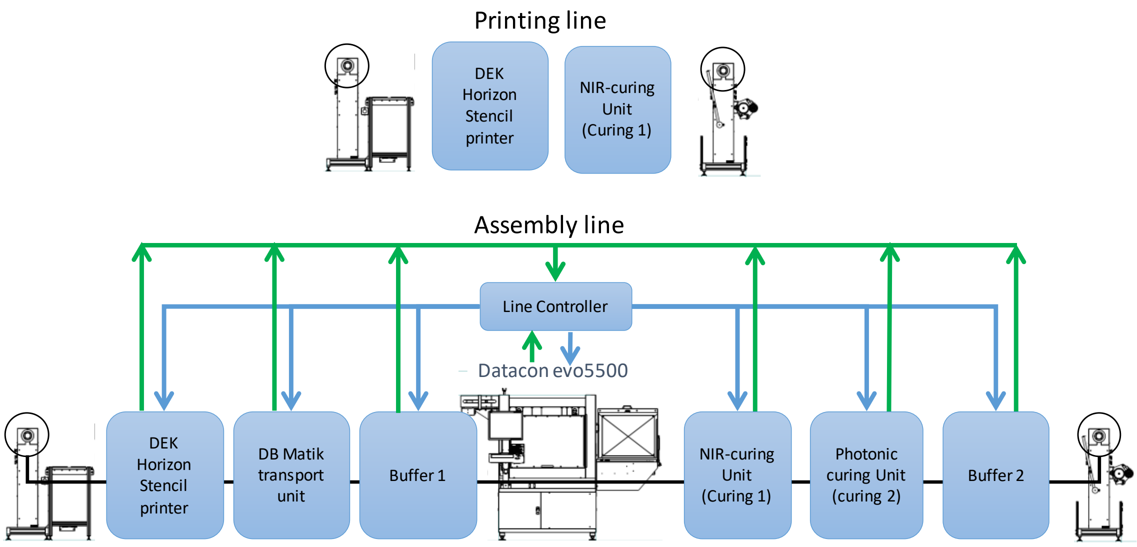

Figure 5: Roll-to-roll flexible electronics line at Holst Centre at the end of the InScope project

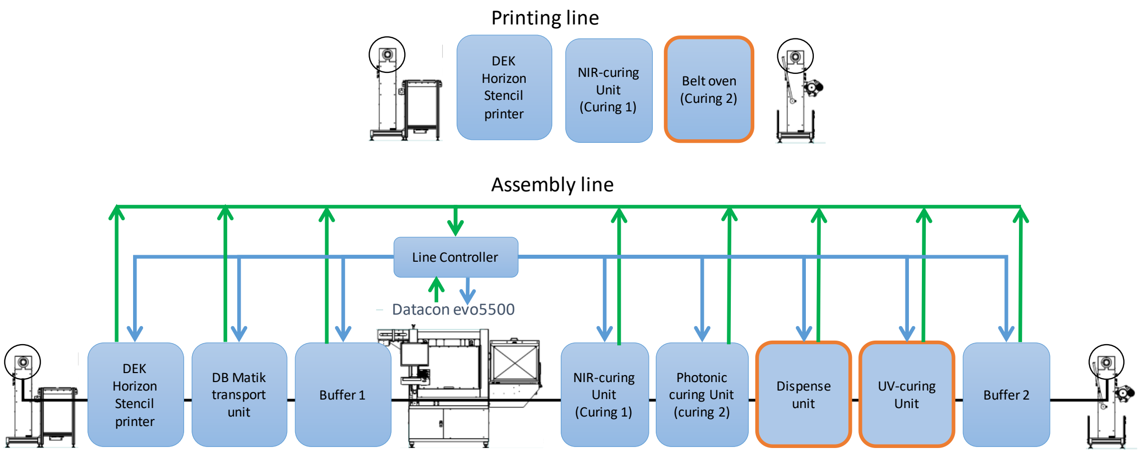

Figure 6: modules added to the roll-to-roll flexible electronics line at Holst Centre in the course of 2022 are indicated by orange lines

The InScope flexible electronics line is continuously being expanded with additional modules. Added modules have only recently been purchased and installed (end of 2021, start of 2022). The purpose of their addition was in particular for projects/tasks/research outside of the TREASURE project. Nevertheless, these modules may be(come) available to produce parts if it favours execution of work for the TREASURE project. The belt oven is currently available as a S2S module, but with adaptations may become part of the printing line.

Roll-to-roll production of IME parts requires an adjusted way of working. In the single-foil approach, that is typically pursued at Holst Centre, components and circuitry are applied to the substrate. The substrate needs to be sufficiently thick (250-500 microns) and reasonably sturdy. A substrate for printed electronics manufactured with the roll-to-roll line needs to be more flexible and thinner (50-150 microns). Applying circuitry and components onto a thinner substrate may cause defects that affect the aesthetics of the part, since the outermost graphic layer is typically glossy black and very fault-intolerant. For the collaboration with EU TREASURE

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partners in WP6, including IME producer WALTER, and realization of a mutual demonstrator, a two-foil approach is thus proposed.

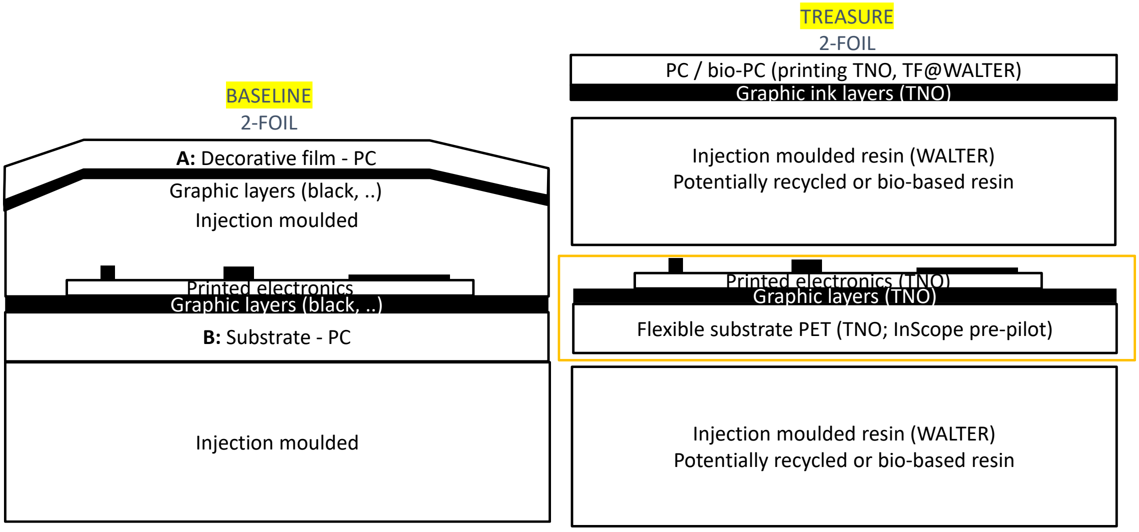

Figure 7: left) baseline 2-foil approach, 3) 2-foil approach as will be followed in future TREASURE activities, e.g. demonstration actions in WP6

The front substrate (PC or bio-based PC by Covestro with a thickness of 250-500 microns) will be printed at TNO and thermoformed at WALTER's facilities. The second substrate will be provided with printed electronics and components by TNO at Holst Centre's facilities. The substrate may be PEN or PET, but also thin PC (175 microns) may be adequate. The latter would favour recycling, as it maintains the mono-polymer layer stacking of the device using polycarbonate as the bulk plastic. Injection moulding for encapsulation of the printed electronics and added rigidity and durability, is also provided by WALTER. The thermoform mould and injection mould need to correspond to the same device design. Creating new moulds is outside of the scope / budget for WP5 activities.

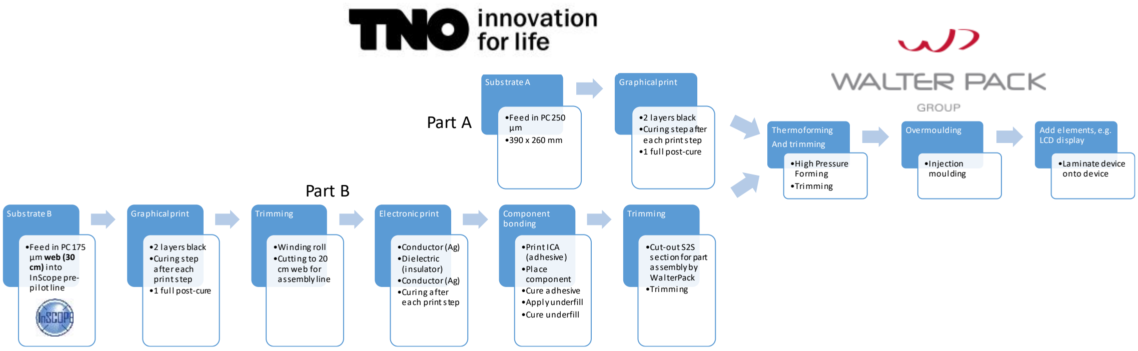

Figure 8: process flow for IME devices created with a 2-foil approach in the EU TREASURE project

2.3.3. Current status and capability of the pre-pilot line

A test run was conducted on the InScope pre-pilot line in Q4 of 2021 and features a multitude of device types, including a small automotive user interface. In particularly printing of a conductive ink and dielectric was tested. The purposes was to assess the quality of the printed layers in the current set-up of the pre-pilot line. The layer stacking consisted of Ag/dielectric/Ag/Carbon/graphic ink. Bonding of SMD components was not done, but the printing did occur on the assembly line (lower part of Figure 6). Focus of the study was the

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printing accuracy of silver layers and insulator, edge definition of all layers, reliability of printed circuitry and definition of layer thicknesses.

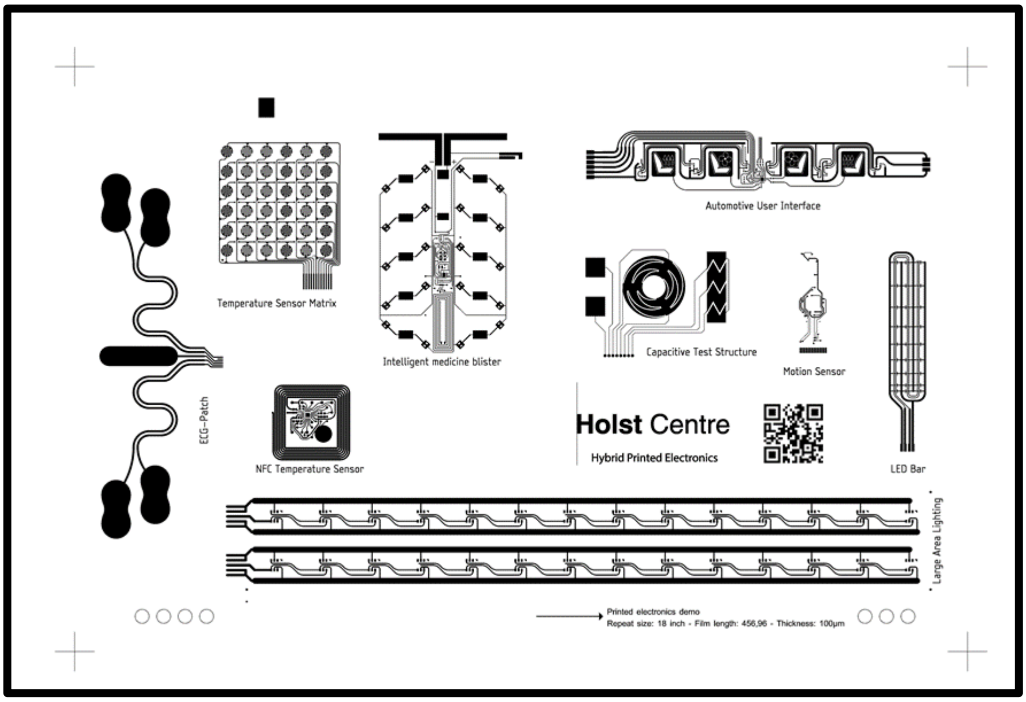

Figure 9: layout of the printed electronics in the R2R test run

Conclusions for this run

- A 5-layer printed electronics design was successfully R2R screen printed
    - Ink throughput seems good, no pinholes were found
    - Alignment was very good
    - Occasionally a small jump was noticed (sudden misalignment); root cause not definite yet
- A 305 mesh with 17% open area and the SCR100 coating was used
    - Resulting prints have rough edge definition
    - Most probably limitation of used screen and emulsion combination
- Minimum design resolution to prevent shorts:
    - Short distance (bond pad) 300 or 200 µm lines with ≥200 µm gap
    - Larger distance (circuitry lines): minimal ≥300 µm gap between lines

For the 2-foil approach presented in Figure 7, a new cylinder needs to be ordered for each printed layer separately to allow rotary screen printing of the necessary design. At first, a design must be agreed upon and has to resemble an electronic car component, based on conventional electronics, for which disassembly is investigated in the TREASURE project (WP3). The climate module was proposed by Seat.

2.3.4. Power consumption of roll-to-roll process

The roll-to-roll line contains many modules for the deposition of graphic and electronic layers. In the next table, the various processes are connected for a S2S process (black circles) and possible R2R process (yellow circles).

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- Handling is manual for the S2S process and semi-automatic in the R2R line; in the R2R line, the webs are unwound and automatically taken through the various stations/modules.
- Printing of graphic layers occurs in much the same way, however, instead of flat bled screen printing, rotary screen printing is used instead in the R2R line. Curing of the wet graphic layers occurs with N-IR lamps but may (once assembled) also occur with a belt oven.
- Stencil printing in the R2R line occurs in much the same way as for the S2S process using stencils. The web proceeds through the line in a stop and go method, which also favours the SMD pick & place processing. Curing proceeds by N-IR and photonic curing. Photonic curing is a high power process but realizes superior properties for the conductive inks. Furthermore, photonic soldering is a patented ultra-high-speed process for bonding of SMDs. The speed more than compensates for the high-power consumption and enables exceptional power savings per part.
- Curing of printed inks occurs in N-IR ovens and with an additional custom-made photonic flash curing unit. Photonic flash curing more intensively cures conductive inks but has also been shown to benefit graphic/dielectric inks.
- Thermoforming and backside filling remains a S2S process. Also lamination remains S2S at our facilities.

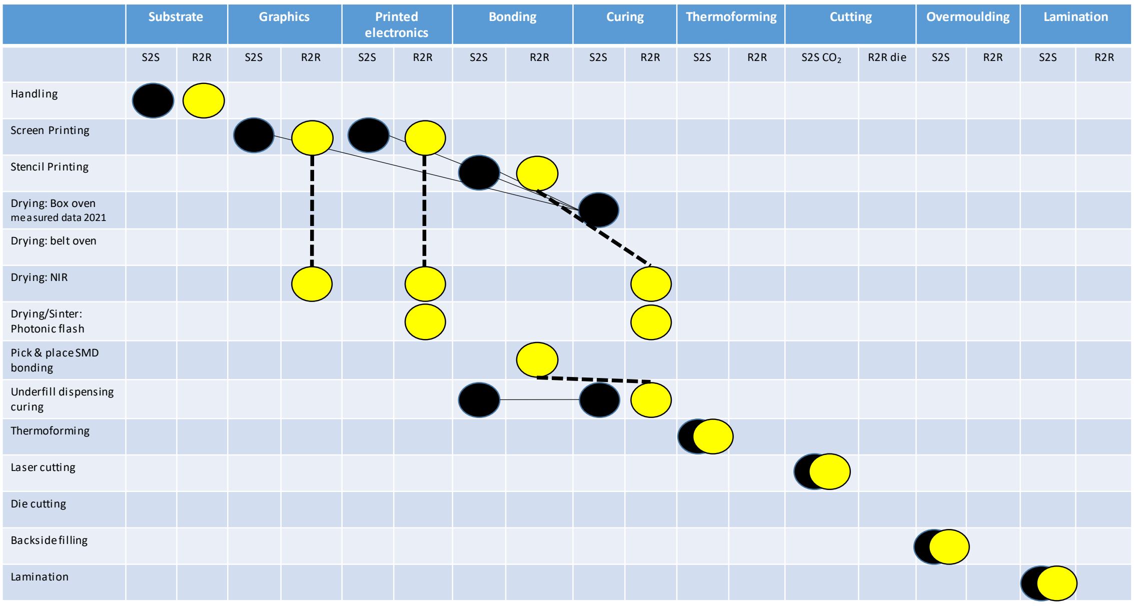

Figure 10: schematic showing current S2S and possible R2R production steps. Yellow boxes correspond to the likely R2R processing steps and black to actual (current) S2S steps

The power consumption of the roll-to-roll process is not well documented at this time and has proven difficult to assess during the first period of the TREASURE project. Early estimates for the power consumption per module are provided below. Additional power measurements are underway but take additional time due to modifications to the high-power grid. Measurements per module separately have not been possible due to the complexity of the high-power cables. Also for safety reasons, a single power measurement device at the clean room level is now pursued.

kW per process		Substrate		Graphics		Printed electronics		Bonding		Thermoforming		Cutting		Overmoulding (kWh/kg)		Lamination	
	Units p.w.	S2S	R2R	S2S	R2R	S2S	R2R	S2S	R2R	S2S	R2R	S2S CO_2	R2R die	S2S	R2R	S2S	R2R
Handling		X	15.2 (max)														
Screen Printing	Graphics:4519 P.Electr.:5478			2.3	4	2.3	4										
Stencil Printing								2.3	10 (max)								
Drying: Box oven measured data 2021				0.3		0.35		0.35									
Drying: belt oven 380 VAC, 16 A, 50/60Hz	22560				10.5 kW (max)												
Drying: NIR	4277 for bonding process – stencil printing, R2R pick & place, NIR drying, UF application and curing				11 (50 kW, 22%)		11 (50 kW, 22%)		11 (50 kW, 22%)								
Drying/Sinter: Photonic flash							Only NP		Only NP								
Pick & place								6.6	2.3								
Underfill dispensing curing								0.1	0.25 / 10								
Thermoforming	21600									14.4 / 34 (max)	??						
Laser cutting	21168											1.2					
Die cutting	86400												2				
Backside filling														0.149	???		
Lamination	43200															8.8	12

Process in HC template calculation

Adaptation to InScope line 2021

Current S2S process

400VAC, 3.3 A, 2.3kVA

Figure 11: power consumption values for the various processes, as are currently available. This data is based on the documentation of the machines and corresponds to kAV values, rather than actual kW values.

S2S production process steps are indicated here in yellow and have been included in more detail and accuracy in Figure 16 (Section 2.4.3).

2.4. Lifecycle analysis (LCA) of IME

The IME technology is still under development and, as a result, its environmental effects and environmental performance in comparison to conventional technologies are not fully known. The full integration and embedding of electronics in plastics has consequences for end-of-life (EoL) processing and probably limits reuse and recycle possibilities considering current EoL processing technologies.

An onset for the full LCA for conventional and IME is provided in this report. It is not complete, and it is not the intention to provide a full answer here. What is provided here, is the life cycle intake, a report of what data has been provided to TREASURE partners, and the outcome of an LCA based on generalized data.

An LCA based on generalized data is highly uncertain: averaging of material profiles (and the use of proxies when the precise dataset is not available), transport, production, recycling, etc, leads to uncertain results. It does not represent a precise picture of the product analysed. A quick indication of influential factors is obtained. However, caution is required. Within TREASURE, the aim for the LCA study is to make a detailed analysis and comparison between IMSE and conventional technology. The analysis was/will be based on primary, high quality data and a very complete profile for the whole life cycle of an IMSE panel and a similar car part produced using conventional technology and modelled with the same data quality.

Moreover, the circularity aspects and EoL processing options will be/were evaluated for both using a recycling process simulation that allows to determine the recycling efficiency and secondary material quality in both cases.

Various publications and work over the past years have enhanced LCA analysis to a simulated-based analysis. This is of importance for especially new product lines for which no inventory data

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exist, or if these do exist are often average and general and have no value for design for recycling. Please consult recent work[2,3] that has combined processing with LCA and exergy to quantify the quality loss of material through the circular economy. TREASURE will thus help to advance the LCA methodology with the detail that is lacking in present LCA analyses especially for new and emerging supply chains. In summary the approach includes all processes in the circular economy of a product/module from primary material production to manufacturing and recycling in full material compositional detail that enables the evaluation of each stream in terms of enthalpy and entropy.

Approach

The environmental performance was calculated through a life cycle analysis (LCA) by TNO CAS (Climate, Air and Sustainability), at the request of TNO Holst Centre, to provide a starting point for further study by MARAS.

Figure 12 illustrates the standard procedure for performing an LCA. In general, an LCA consists of (1) determining the goal and scope, (2) the inventory phase, with definition of the product system and quantification of inputs and outputs in terms of a functional unit, (3) characterization of the inventory as environmental effects, normalization and weighting of results and (4) interpretation of results and conclusions.

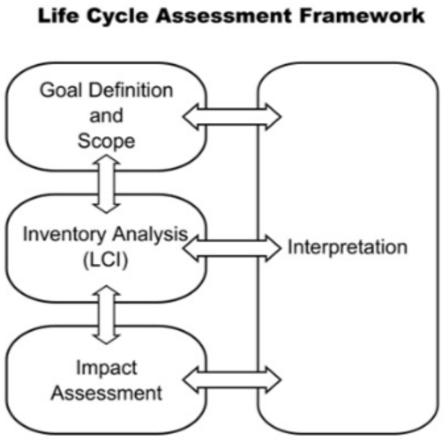

Figure 12: Standard procedure in a Life Cycle Assessment

The goal and scope of this study (step 1) have been determined by Holst Centre. For step 2 (data collection), primary data from technical data and material safety sheets was used to model the foreground processes alongside information openly available. Ecoinvent 3.6 datasets were used to close data gaps and model background processes.

The method used for quantifying environmental impact was the ReCiPe 2016 method[i], midpoints, as well as endpoints. The Recipe method comprises three end-point categories, 1) damage to human health, given as Disability Adjusted Loss of Life Years (DALY), 2) damage to ecosystem quality, given as loss of species per year (species.yr), and 3) damage to resource availability, given as surplus cost ($), and 17 mid-point categories, which comprise Global Warming Potential, Human Toxicity and Freshwater ecotoxicity, among others.[i]

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[2] N Bartie, L Cobos-Becerra, M Fröhling, R Schlatmann, M Reuter, Metallurgical infrastructure and technology criticality: the link between photovoltaics, sustainability, and the metals industry, Mineral Economics, 1-17 2022

[3] M.A. Reuter, A. van Schaik, J. Gediga (2015): Simulation-based design for resource efficiency of metal production and recycling systems, Cases: Copper production and recycling, eWaste (LED Lamps), Nickel pig iron, International Journal of Life Cycle Assessment, 20(5), 671-693.

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The results are presented as characterized results for selected midpoint categories, as well as contribution to damage assessment (endpoint) categories.

The calculations performed in this study follow the procedures as described in the NEN-EN-ISO 14040-2006 standard[4].

The following settings have been explicitly used for the calculations:

- Capital goods (infrastructure) have not been included in the calculations.
- Long-term emissions have not been included.

Data sources:

- IME console: Detailed primary data from technical data and material safety sheets has been used in the modelling.

2.4.1. Goal and scope

The goals of this study were to determine:

LCI:

- A full life cycle intake including as much data on the materials (e.g. composition) as possible
- A full list of process steps and power consumed
- A detailed overview of losses during production (waste)

LCA:

- The dominant contributors to environmental impacts, i.e. hot-spots regarding material usage and/or energy of the IME device

This analysis was executed within the following scope:

Geography

The processes included for the treatment, transport and production are specific to the IME console produced in the Netherlands.

Time and technology

In this study the environmental effects were calculated based on a lab-scale produced IME device. A more optimal production line is expected at an industrial scale, which would provide for a more efficient substrate preparation, thermoforming and curing, demanding less energy and less material per unit produced. Hence, this study should be broadened to include upscaling effects in case this analysis is also applicable to the environmental impacts of such a product at an industrial scale.

The results reported in this study are relevant for the time frame between the years 2020 and 2024, since the car industry is a fast-paced sector that tends to roll out new technologies relatively quickly. This means that the comparison with the conventional console tends to get

[4] Huijbregts, M., Steinmann, Z. J. N., Elshout, P. M. F. M., Stam, G., Verones, F., Vieira, M. D. M., … van Zelm, R. (2016). ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. National Institute for Public Health and the Environment, 194. https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

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outdated in just a few years. The same is valid for printed electronics, which is also under development and rapidly evolving.

Data quality, completeness and consistency

The focus in this project was on the integrated electronics-specific parameters, which the technology developers can influence to improve sustainability. To that end, a detailed analysis of the materials used in the console production was performed. The panel composition was determined with the help of technical data and material safety sheets, as described earlier. Next, the substances composing the materials used in the console production were connected to EcoInvent datasets or Plastics Europe data, e.g., in the case of Polycarbonate and Epoxy. Where a dataset was not available, a proxy was used. This was the case for five of the 16 mapped substances. The same treatment was applied to the other stages of the console life cycle.

The inventories for raw material extraction and console production are described in sections Table 1, Table 2 and Figure 16. The EoL treatment scenario that is in preparation is based on common practice and publicly available data from literature.

The data quality, completeness and consistency for EoL will be improved this year by MARAS. They will perform a simulation for the recycling process of an IME console using the data collected for the LCI as input. For this IME device, a detailed compositional detail of its modules will provide, and, depending on results, obtained product redesigns can be suggested. Especially of interest is the "unmixing" of materials into materials of sufficient quality that these can find their way back into the product. Realistic and viable solutions will be offered to show if this is at all possible, and if not suggest for example energy recovery to treat complexly linked different polymer materials.

2.4.2. Life cycle system boundaries

In our early life cycle assessment, we focused on raw materials and IME part production. Electronic components have not yet been accounted for. Within TREASURE, this will be included by a study using an commercially available open-source PCB by Arduino. At the time of writing, this study is underway, and the results cannot be included in this LCA. Transport of raw materials, SMDs and PCBs from the producer to TNO's facilities where the IME part is made, is not included. Transport is difficult to assess correctly; actual production locations of said materials are unknown. Method of transportation is also unknown. Production of IME parts is included (see Figure 4 and Figure 16 for information on the process flow and power consumption of the S2S process) with exception of the moulds for thermoforming and injection moulding. The reason is that we consider a rather small number of samples. The moulds would in this case dominate the outcome of the LCA. In typical high-volume production, the impact of the moulds would be spread over tens, if not hundreds of thousands of units. End-of-life is also excluded at this point: generalized descriptions for incineration and recycling do not contribute to the goal of this study as only general EcoInvent datasets are available. These are generic datasets that do not accurately represent the expected EoL of this console. An accurate representation/calculation of EoL environmental benefits and burdens requires MARAS' expertise and will use process simulation models to quantify the EoL recyclability and purity of materials possible. A comparison is nevertheless quite interesting in order to determine the improvement to the accuracy when using MARAS' approach to EoL.

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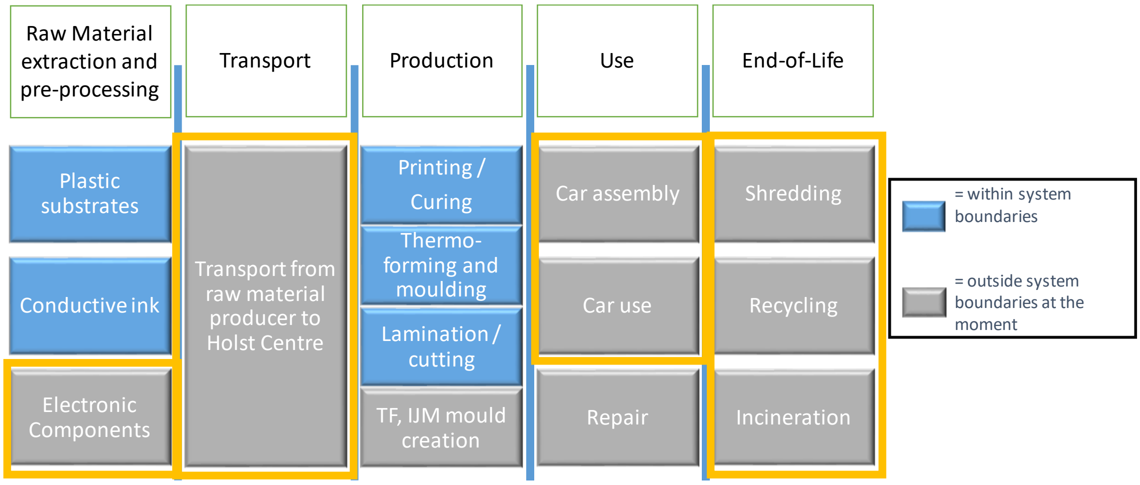

Figure 13: System boundaries for the IME device. Blue boxes represent processes within the system boundaries while grey boxes represent the processes left out of the system boundaries. Orange encircled boxes will be the focus of further study/quantification

2.4.3. Life cycle inventory (LCI)

This section describes the quantification and modelling of each process in the production and and the materials. The databases used for this are Ecoinvent 3.6 together with Industry Data 2.0 (created by PlasticsEurope), where available, for the plastic components. Where PlasticsEurope data was available, it was preferred over the Ecoinvent data, as their dataset is based on direct industrial data and therefore assumed to be more accurate and representative than the Ecoinvent alternative.

Simulation-based approach will quantify the LCI for the EoL of the products and especially also highlight the achievable material quality achievable.

2.4.3.1. Raw material extraction

A summary of the materials and energy used in the production process is given in Table 1. The amounts also include the material loss inherent to the production process (e.g. trimmings, margins, etc.). See Figure 4 for the process flow. Extensive weight tables, MSDS and waste calculation is provided in a separate Excel sheet.

Table 1: BOM for touch panel (solids only)

Bill of materials		
Solid material	Weight per product incl waste (g)	
polycarbonate		
Substrate	44.0	Waste ~ 50% due to S2S processing
Backfill	217.8	Waste ~20% due to low series production
TiO_2 in backfill	24.2	“ “
TPU adhesive	0.4	10% cutting waste assumed
Graphics black	1.76	Dry weight matrix, 63% waste
Carbon colouring	0.45	Dry weight colouring, same waste
Graphics white	1.4	Dry weight matrix, 68% waste
TiO_2 colouring	1.4	Dry weight colouring, same waste
Graphics blue	0.6	Dry weight matrix, 67% waste

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Cu-complex colouring	~0.0	Dry weight colouring (0.5%), same waste
Ag	0.3	Dry weight, 10% waste on printing
dielectric	1.3	Dry weight, 98% waste on printing
ICA baseline	~0.0	Dry weight conductive adhesive, ~10% waste
UF baseline	~0.0	Dry weight underfill, ~0% waste
Total for panel	294	
Total Ag in panel	0.3(4)	

It should be noted that the waste for some materials is quite high. This in inherent to research-scale sheet-to-sheet production. The polycarbonate is processed with a size of 390x260 mm^2 and fits only a single panel, resulting in high cutting losses. Losses resulting from screen printing are even higher; in some cases about 98% of the material is lost. To wet the screen, and to keep it sufficiently wet during processing of the rest of the batch, a minimum amount of ink is needed, say 30 g of dielectric ink. Of this material, only a limited amount ends up on each device (0.03 g). The remainder of the 30 g can be used to coat the other 19 devices (when a limited series of 20 devices is considered). Due to additives (e.g. thinner), the remaining ink is not returned to its original container. If no reactive additives (e.g. catalysts) are added, as is the case for graphic inks for white, black and blue layers, then the remaining ink can be used at another time. As a result, the waste for dielectric ink may have been very much overestimated. For the blue, black and white graphic inks, the waste is quite accurate, as the added volume that is necessary to keep the screen wet, is lost. In addition, it should be said that with rotary screen printing and a full-continuous process, these losses will go down considerably.

Various materials, except the TPU adhesive, polycarbonate, ICA baseline and UF baseline were applied as ink, leading to significant solvent usage (8 w/w-% per panel). Extensive weight tables, MSDS and waste calculation is provided in accompanying Excel sheet.

Table 2: BOM for touch panel (solvents only)

Bill of materials		
Material	Weight per product (g) incl waste	Solvent, as described in MSDS
Ag	0.14	(2-Methoxymethylethoxy)propanol
Dielectric	0.15	4-Hydroxy-4-methylpentan-2-one
Dielectric	0.05	Triethyl Phosphate
Graphic black	1.22	Hydrocarbons, C10, aromates, < 1% naphta
Graphic black	1.06	Solvent naphtha (petroleum), light arom.
Graphic black	0.02	Naphtalene
Graphic white	1.64	Solvent naphtha (petroleum), light arom.
Graphic white	0.18	Naphtalene
Graphic blue	0.43	Hydrocarbons, C10, aromates, < 1% naphta
Graphic blue	0.45	Solvent naphtha (petroleum), light arom.
Graphic blue	0.01	Naphtalene
Variowash for screen cleaning		
Variowash	7.95	Solvent naphtha (petroleum), light arom., benzene content: <0,1%

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Variowash	7.95	1-methoxypropane-2-ol
Variowash	2.27	2-methoxy-1-methylethylacetate
Total weight	23.5	8% (w/w) of panel (incl waste)

In above table, a cleaning solution Variowash is added. Variowash is used to clean the screens after an ink is used. With rotary screen printing and a full-continuous process, the losses will go down considerably and the use of variowash is minimized.

2.4.3.2. Production steps

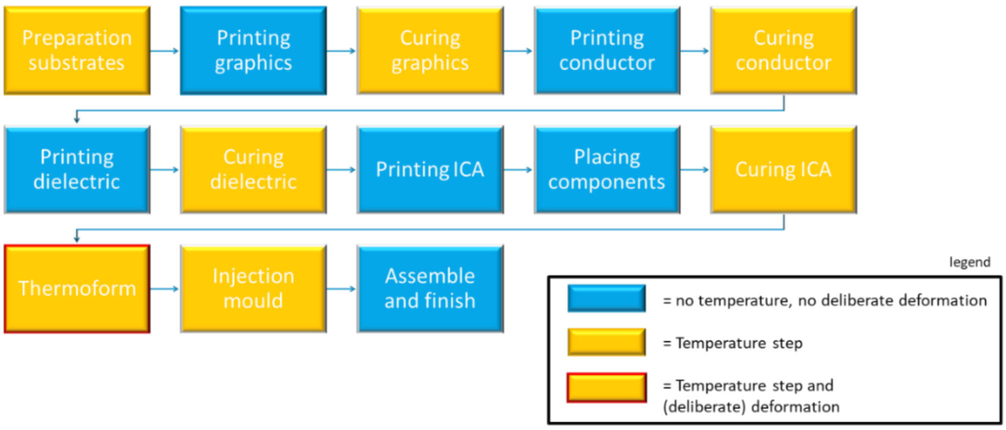

Figure 14: production process of the IME touch panel

The integrated electronics production process was performed in the following order:

1. printing and curing of graphic inks
2. printing and curing of conductive inks and dielectric
3. bonding of SMD components
4. high pressure thermoforming in order to receive its final shape
5. injection moulding, the (envisioned) final step in the process, which encapsulates the printed electronics and provides additional rigidity and ankers for further assembly of the part in the car.

A general overview of the production process of an IME part is provided in Figure 14. In Figure 15, this production process is more specific for the IME part that is considered in the LCA: the coffee machine interface panel.

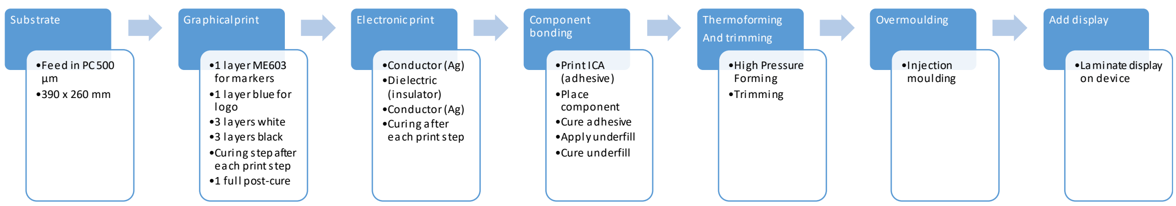

Figure 15: process flow for single-foil IME (repeat of Figure 4)

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2.4.3.3. Power consumption

For the total power consumption of the S2S process, the various steps were laid out and quantified. The power consumption per process was either measured or estimated based on the specifications of the apparatus. Curing with a Venti oven, for instance, was subjected to measurements, as curing was believed to be one of the more power consuming production steps. Also the serial production (1 plate printed per minute and subsequent delay in completing the whole batch, namely ~50% additional curing time) was taken into account. Thermoforming, lamination and injection moulding could not be measured, unfortunately, and were either estimated using the apparatus specifications (lamination, thermoforming) or using a literature study[5] (IJM). At present, we are installing high power meters in the clean room for the purpose of quantifying these machines.

power consumption per IME device							50% extra due to	total		*comments*
layer type	*step*	kW	hrs	kWh/step	# dev	kWh/device	overlap for oven filling	kWh/device	kg CO2 eq	grey electricity NL
ME603	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.735	0.33	0.25	10	0.02	0.01	0.04	0.02	per 10 plates, with overlap to get to 10
Blue graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
White graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
White graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
White graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
Black graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
Black graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
Black graphic	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.17	0.08	10	0.01	0.00	0.01	0.01	per 10 plates
POSTCURE	cure	0.49	4.00	1.96	10	0.20		0.20	0.13	per 10 plates
ME603	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.735	0.33	0.25	10	0.02	0.01	0.04	0.02	per 10 plates
dielectric	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.49	0.33	0.16	10	0.02	0.01	0.02	0.02	per 10 plates
ME603	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
	cure	0.735	0.33	0.25	10	0.02	0.01	0.04	0.02	per 10 plates
ICA	print	0.69	0.017	0.01	1	0.01		0.01	0.01	per plate
SMD	pick & place	1.5	0.01	0.01	1	0.01		0.01	0.00	
ICA	cure	0.735	0.17	0.12	10	0.01	0.01	0.02	0.01	per plate, 73 comp, 0.4 s/comp
UF	dispense	0	0.00	0.00	1	0.00		0.00	0.00	per plate
	cure	0.735	0.17	0.12	10	0.01	0.01	0.02	0.01	per 10 plates
thermoform	Niebling	13.6	0.01	0.11	1	0.11		0.11	0.07	per plate
cutting	Trotec laser	1.2	0.02	0.02	1	0.02		0.02	0.01	per plate
injection mould				0.13	1	0.13		0.13	0.08	per plate, from lit.
laminate	Optek lam.	8.8	0.13	0.15	1	0.15		0.15	0.10	per plate, for LCD
				4.24		**0.93**		**1.02**	**kWh**	
									0.66	**kg CO2 eq**

Figure 16: power consumption for sheet-to-sheet production of single-foil IME-based coffee machine interface panel

2.4.4. LCA results

The results from the calculation with SimaPro will be described in this section. As shown in Figure 13, the SMDs and PCBs are excluded from the calculation at this point. The IME part is driven by separate PCBs. However, the PCBs are commercially obtained and are not specifically described in literature. It is known that the production of a PCB has quite a big impact on the environment, with global warming potentials of 18.6-39.2 kg CO^2 eq per m^2, without considering the SMD components[Errore. Il segnalibro non è definito.]. SMD diodes were found to contribute 2.92-3.54 10^{-1} kg CO_2 eq per gram of diode[ii]. Although SMD components are fairly light, this still builds up to 1-2 kg CO_2 eq per part for 50-100 SMD components. Due to the added challenges regarding external PCBs and the various SMD components, we excluded these from this analysis and focused primarily on the production process of the IME plastic panel itself. UNIVAQ is examining PCBs

[5] Elduque, A. et al., Materials 2018, 11, 1740, doi:10.3390/ma11091740, apparatus 4 from table 3 and 4

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and SMDs at this time (TREASURE WP5) and may provide useful information that will allow a full description for a conventional part and an IME part with PCBs and SMDs in the future.

The endpoint analysis was used to objectively select the most relevant midpoint categories for detailed analysis. Figure 17 and Figure 18 show the absolute and normalized values of the calculations. Table 3 displays all the material and process contributions with calculated values for the 18 mid-points. The most impactful contributions are displayed in red with a gradient colouring towards the smallest in green. The major contributors are clearly PC backfill and power consumed for the global warming potential (kg CO_2 eq), and Ag and PC backfill for terrestrial ecotoxicity. While typically the global warming potential is provided in public LCA studies for IME[iii], it is clear that other mid-points should not be overlooked.

Table 3: LCA results, including raw material impacts and device fabrication

Raw materials + production Impacts														
	function													
Values	TPU adhesiv	Ag	PC backfill	Dielectric	Graphic black	Graphic blue	Graphic whit	Isotropic con	Variowash sc	PC substrate	Underfill	Total Raw	Electricity	Injection r
Global warming	2.35E-03	1.06E-01	8.92E-01	7.39E-03	1.16E-02	3.79E-03	1.54E-02	2.54E-04	3.87E-02	1.53E-01	1.24E-06	1.23E+00	6.48E-01	6.26E-02
Ozone formation, Human health	5.11E-06	9.02E-04	1.30E-03	1.62E-05	2.81E-05	9.45E-06	3.97E-05	2.17E-06	9.58E-05	1.91E-04	2.90E-09	2.59E-03	3.44E-07	4.13E-08
Ozone formation, Terrestrial ecosyste	5.34E-06	9.14E-04	1.34E-03	1.70E-05	2.95E-05	9.92E-06	4.14E-05	2.19E-06	1.02E-04	1.98E-04	3.28E-09	2.66E-03	3.63E-03	6.16E-04
Terrestrial acidification	9.42E-06	7.37E-04	2.84E-03	3.00E-05	5.38E-05	1.89E-05	1.44E-04	1.77E-06	1.49E-04	1.75E-04	3.56E-09	4.16E-03	8.16E-04	1.93E-04
Human carcinogenic toxicity	2.32E-05	3.00E-03	2.76E-03	8.34E-05	1.06E-04	3.94E-05	1.44E-04	7.19E-06	3.37E-04	3.13E-04	6.63E-09	6.82E-03	2.98E-04	1.24E-04
Stratospheric ozone depletion	1.27E-08	1.33E-07	2.33E-07	3.80E-08	5.39E-08	1.86E-08	4.31E-08	3.20E-10	3.35E-08	3.67E-08	2.42E-13	6.04E-07	8.26E-04	2.14E-04
Ionizing radiation	1.38E-05	9.90E-04	9.51E-03	4.36E-05	1.33E-04	4.27E-05	1.43E-04	2.36E-06	6.12E-04	1.71E-03	3.52E-09	1.32E-02	8.99E-04	2.67E-04
Fine particulate matter formation	3.79E-06	3.35E-04	8.94E-04	1.21E-05	2.10E-05	7.21E-06	4.86E-05	8.04E-07	6.51E-05	5.49E-05	1.56E-09	1.44E-03	3.63E-05	2.49E-06
Freshwater eutrophication	1.58E-07	3.30E-05	1.15E-05	4.90E-07	6.58E-07	2.39E-07	8.98E-07	7.93E-08	1.72E-06	9.34E-07	4.09E-11	4.97E-05	1.56E-06	1.93E-06
Marine eutrophication	1.46E-07	2.67E-06	1.68E-05	4.37E-07	5.89E-07	2.07E-07	8.81E-07	6.40E-09	4.13E-07	1.81E-06	1.94E-11	2.40E-05	3.36E-01	2.57E-01
Terrestrial ecotoxicity	6.04E-03	7.77E-01	5.11E-01	1.93E-02	3.47E-02	2.05E-02	4.26E-02	1.86E-03	1.44E-01	2.34E-02	3.04E-06	1.58E+00	1.17E-04	1.60E-04
Freshwater ecotoxicity	4.24E-06	1.16E-03	2.89E-03	1.34E-05	2.08E-05	9.79E-06	1.63E-04	2.77E-06	3.57E-05	4.06E-05	1.16E-09	4.33E-03	7.03E-04	3.56E-04
Marine ecotoxicity	6.53E-06	6.79E-02	4.26E-03	2.11E-05	4.24E-05	2.12E-05	2.36E-04	1.63E-04	1.42E-04	9.44E-05	2.41E-09	7.29E-02	1.96E-03	9.75E-04
Human non-carcinogenic toxicity	4.70E-04	1.50E-01	1.37E-01	1.56E-03	2.26E-03	1.23E-03	6.62E-03	3.60E-04	1.18E-02	9.37E-03	1.80E-07	3.21E-01	1.01E-01	1.65E-02
Land use	2.75E-04	9.17E-03	1.60E-02	8.42E-04	1.12E-03	3.88E-04	1.24E-03	2.20E-05	8.23E-04	1.82E-03	1.35E-08	3.18E-02	1.29E-02	3.57E-02
Mineral resource scarcity	7.21E-06	3.07E-02	2.13E-02	2.73E-05	3.68E-05	1.57E-05	1.20E-03	7.36E-05	1.52E-04	1.97E-05	3.88E-09	5.35E-02	4.33E-04	1.12E-03
Fossil resource scarcity	8.99E-04	2.81E-02	4.38E-01	2.88E-03	7.16E-03	2.31E-03	6.67E-03	6.74E-05	2.60E-02	8.15E-02	5.07E-07	5.94E-01	1.76E-01	3.13E-02
Water consumption	5.71E-05	8.11E-04	7.67E-03	1.82E-04	2.35E-04	8.14E-05	4.04E-04	1.98E-06	9.26E-04	7.16E-04	2.57E-08	1.11E-02	5.14E-03	1.73E-03

The final column in Table 3 is the additional impact of thermoforming and injection moulding aside from power consumption. Ecoinvent describes separate impacts coming from e.g. warming of the direct environment, cooling water, etc.

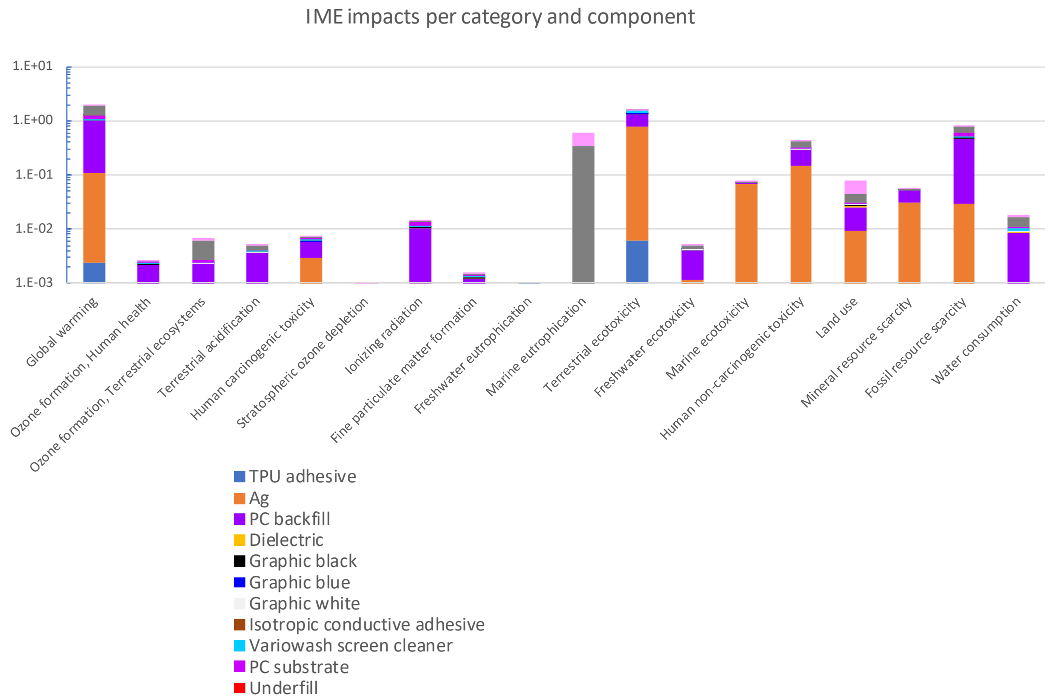

Figure 17: mid-points (h) per category and component for the IME panel (absolute values, log scale)

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The environmental impact hotspots identified in this analysis were electricity consumption during the production phase, the polycarbonate used in the backfill and the substrate, the silver in the conductive ink and titanium dioxide used in the backfill colouring. These 4 components of the console production amount to 80% or more of the impacts for all categories, except for Marine Eutrophication and Land use to which they amount to 57% and 48% respectively.

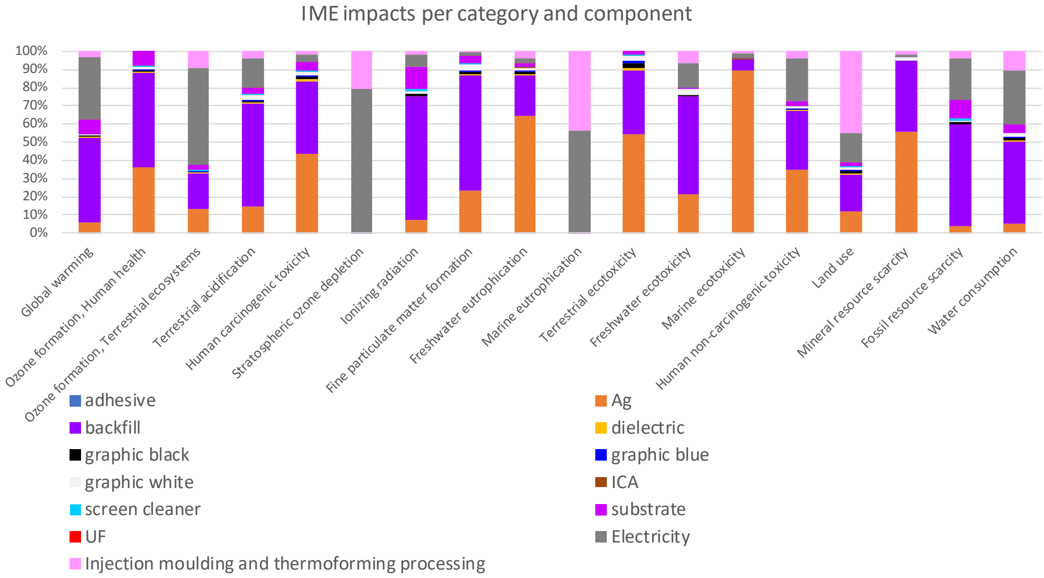

Figure 18: mid-points (h) per category and component for the IME panel (normalized values)

The main culprits of the environmental impacts of electricity consumption during panel production can be found in Figure 19.

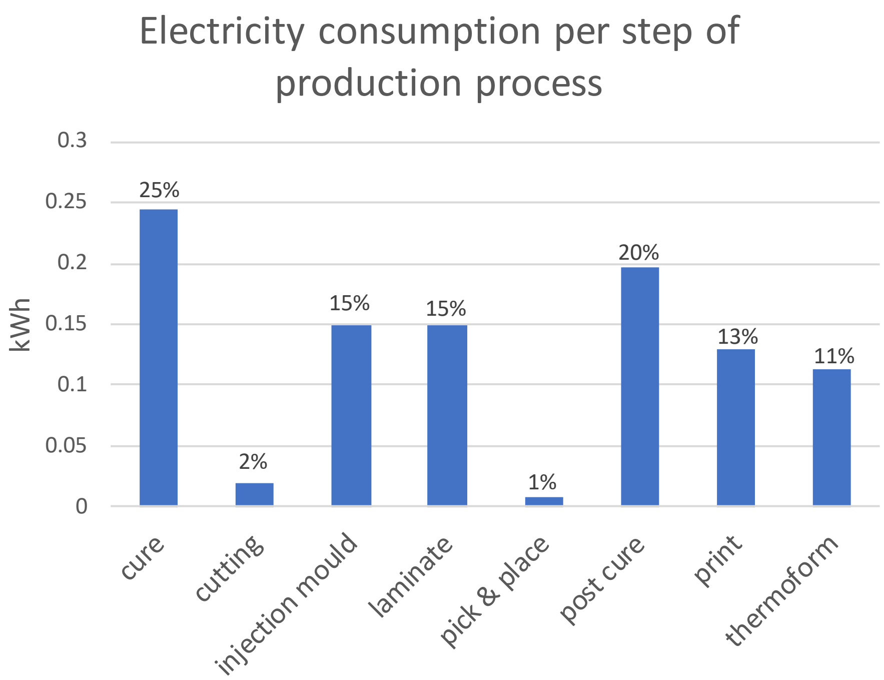

Figure 19: Electricity consumption in kWh per product and per process for the IME panel

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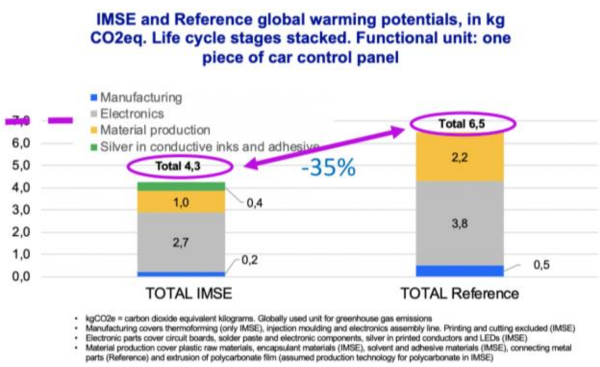
The curing process has the highest consumption, with 45% of all the energy used to produce a console. For a large part this is due to the post-cure of 4 hours for all graphic inks combined. With a faster drying ink, different chemistry for the ink, or a different method of curing, this contribution can be reduced. Interestingly, Tactotek described in its LCA in 2019 for IMSE[6] that printing and cutting could be omitted, as it is assumed that these are negligible in comparison to thermoforming and injection moulding. This was repeated in their webinar of 2022[8]. In our case, this cannot be done for curing.

The characteristic forming processes for IME, thermoforming and injection moulding, roughly account for the same value as curing (26% in total). Injection moulding was not done at TNO for this panel, but by a third party, and as such values for IJM were taken from a literature study by Elduque *et al.*[7] We used a value of 0.6 for the SEC (kWh/kg injected resin) to obtain 0.13 kWh, based on IJM machine 4 from table 3 in Elduque *et al.*

a) 

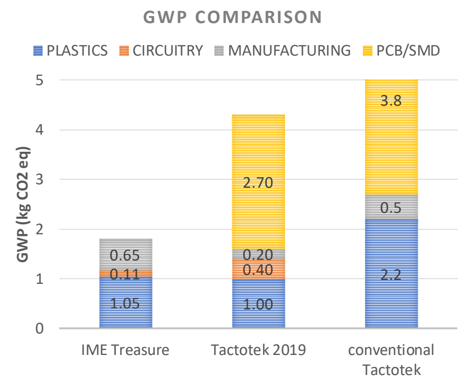
b) 

Figure 20: a) LCA by VTT at the request of Tactotek[6], b) comparison of the LCA in this report and the Tactotek LCA for panels based on IME and conventional electronics[8,8]

Figure 20 shows a comparison of our results and those presented by Tactotek. The products are roughly the same in size, but the approach differs somewhat. The comparison should thus be considered as a rough indication and confirmation that our calculation is in the correct order of magnitude for IME panels. As stated, there are some crucial differences, as printing and curing was omitted by Tactotek, while in our case, the contribution of curing to the power consumption is quite large. Further details of Tactotek's LCA were not found.

After this initial LCA calculation, we repeat that it is based on approximations and generalizations which is the common procedure for screening LCAs. In the remainder of the TREASURE project we wish to develop a detailed and more accurate analysis based on primary data focusing on:

- Expanding this LCA with the missing sections
  - SMDs, PCBs, with the help of analysis on these elements by UNIVAQ
  - Estimation for transport
  - Description and inventory of the use phase, with the help of SEAT

[6] Tactotek presentation, Harvela, J., Industry Summit 2019, High Level Process, https://industrysummit.fi/wp-content/uploads/2019/05/12_Jussi-Harvela_Tactotek_14_40.pdf
[7] Elduque, A., Elduque, D., Pina, C., Clavería, I. and Javierre C., "Electricity Consumption Estimation of the Polymer Material Injection-Molding Manufacturing Process: Empirical Model and Application", Materials 2018, 11, 1740; http://doi.org/10.3390/ma11091740
[8] Tactotek webinar IMSE™ Sustainability, 24 feb 2022

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- ○ End-of-life (EOL) with a few recycling scenarios modelled using generalized data from EcoInvent database and assumptions
- More in-depth approach to LCA/EOL with the help of MARAS
  - ○ By the use of simulation-based approach which includes processing flowsheets for EoL treatment of products and modules will be applied to understand the EoL environmental performance and true losses from the system. The process simulator is also linked to openLCA using Ecoinvent.
  - ○ The produced LCI including all compositional detail will provide true recyclability performance of the products (see[9,10]).
  - ○ This provides the detail for realistic design for recycling and EoL options (or not).
  - ○ Of special interest is the unjoining of intimately linked materials into materials of a quality equal to and thus recyclable back into the same product.

2.5. IME design for recyclability

From the LCA it is clear that silver and polycarbonate are two important materials that should be targeted for recycling. TNO has patented an approach that targets disassembly of IME in such a way that these major contributors to the environmental impact can potentially be recycled. In a most ideal case, we could potentially see a closed loop manufacturing scheme. Closed loop manufacturing does require highly pure waste streams, as recycled materials need to exhibit identical properties ((thermo-)mechanical, e.g. softening point, hardness, stiffness, etc) and appearance. Contaminants may quickly deteriorate such material characteristics. Since IME panels are made to fully encapsulate printed electronics, SMDs and printed graphic inks, achieving pure waste streams, and hereafter pure precursors for new IME devices, is a major technical challenge. At present, only laboratory samples have been made.

Our approach is still in its infancy, but we focus on a combination of photonic debonding and mechanical disassembly. After establishing a way of working on a laboratory scale, we hope to expand our efforts to injection moulded devices, and an exploration of alternative / semi-automated disassembly routes.

Figure 21: photonic debonding of an IME device

[9] M.A. Reuter, A. van Schaik, M. Ballester (2018): Limits of the Circular Economy: Fairphone Modular Design Pushing the Limits, World of Metallurgy - ERZMETALL 71(2), pp. 68-79.

[10] M.A. Reuter, A. van Schaik, J. Gutzmer, N. Bartie, A. Abadías Llamas (2019): Challenges of the Circular Economy - A material, metallurgical and product design perspective. Annual Review of Materials Research, 49, 253-274.

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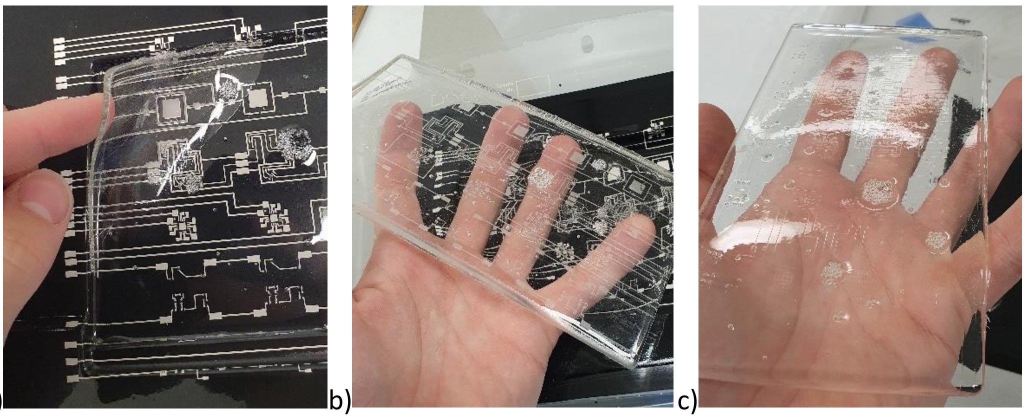
Photonic debonding is a method that uses high intensity light flashes to cause delamination through the formation of a blister at the interface of the substrate and the black graphic ink. The flashes have a very high intensity and cause abrupt heating without dissipation of heat. As a result, a blister forms that disrupts adhesion of the graphic layer to the polycarbonate substrate over a large area in our current setup (~100x50 mm^2). Visible in the picture above is that the PC substrate was detached from the remainder of the IME device. With a bit more cleaning, for instance with iso-propanol, a film was obtained with a small residual absorption from the former black coating. The magnitude of contamination is still to be examined.

In a next stage, the backside filling needs to be detached from the printed electronics. We managed to find a method to weaken the otherwise strong adhesion of PC to the black graphic ink layer and the printed electronics. The reference sample without the weakened adhesion, proved very difficult to disassemble. Aside from a high effort to disassemble, also the outcome varied. This would make it hard to disassemble the device in such a way that e.g. the Ag can be reliably recovered.

Figure 22: manual disassembly of an IME device with different results: a) rupture at the interface of PC and graphic ink, b) rupture at various interfaces

In our first trials with our solution to the problem, we managed to release the epoxy backfill. The epoxy backfill was used since IJM was not available at TNO for this device design. What is shown in Figure 23 is the peeling of the epoxy backside layer of a few mm thick and subsequent washing of both the substrate and the backfill. This resulted in a clean backfill. We hope this process translates well to injection moulded samples without compromising the reliability of the device too much. It was noted by Maras that a large gain in sustainability due to an improved recyclability may counter the reduction in reliability caused by an eco-design, and it is likely that our efforts will have to focus on finding a balance in these two contributors to sustainability. To allow a further study with injection moulded polycarbonate, a switch is necessary to a design that does not allow thermoforming. This study is underway.



a) b) c)

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Figure 23: manual disassembly of the backside of an IME device: a) removal of the epoxy backfill, b) showing the Ag/epoxy interface, c) clean epoxy interface after washing

A combination of before mentioned methods allowed us to fully disassemble a device, such that a centre section is obtained with exposed Ag alongside polycarbonate substrate and backfill. While the frontside is still contaminated with residual black graphic ink, due to an incomplete debonding process, the backside is clean. Photonic debonding still requires further optimization, but the potential of the process is clearly visible; a 400-microsecond flash was sufficient to allow the centre part to be conveniently removed from the substrate. The exposed silver can be recovered by metallurgic processes, as investigated by UNIVAQ in the TREASURE project.

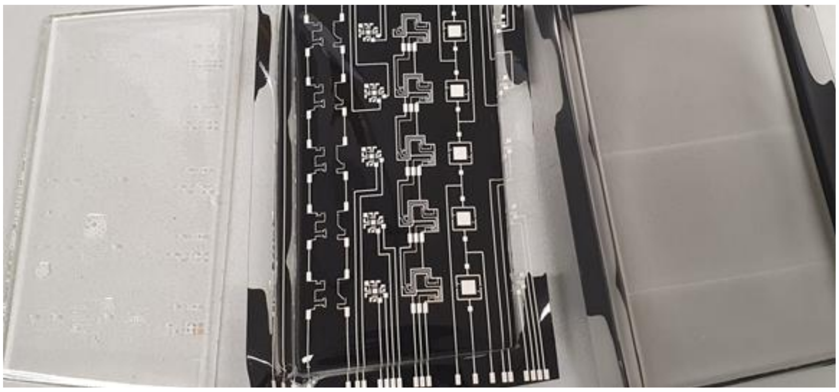

Figure 24: manual disassembly of the backside of an IME device: a) removal of the epoxy backfill, b) showing the Ag/epoxy interface, c) clean epoxy interface after washing

In the next period, the following actions are planned:

Design for recyclability

- Further explore alternative designs, approaches and disassembly techniques

Injection moulded IME devices

- Work on a design together with TNO Brightland Materials Centre (BMC), coming from the (closed) Interreg project Flexlines, to determine the applicability of the design for recyclability in injection moulded devices
  - Test printed electronics functionalities
  - Disassemble under controlled conditions
  - Quantify the adhesion strength of injection moulded PC on the weakened graphic ink interface

Ag recycling

- Printing of a specific Ag ink and combine efforts with UNIVAQ and the ink supplier to examine closed-loop manufacturing with recycled Ag ink

PC recycling

- Examining the residues on photonic debonded polycarbonate substrates
- Determine the purity of the PC waste stream
- Optimize the photonic debonding process
- Recycle PC obtained from our dismantling trials in new IME samples, realized together with BMC

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3. Conclusions

In task 5.5 activities, the printed electronics (InScope) pre-pilot line was examined, tested and its process simulated to allow the manufacturing of In-mould electronics. The various modules of the line were found to (still) function properly. The power consumption is provided in this report, however, the data is largely based on equipment specifications, rather than actual measurements. These measurements require cleanroom modifications, which are on-going. It is expected that these will be finished before the summer recess.

An in-mould electronics device has been studied for its environmental impact. While the lifecycle assessment was only done in part at the time of writing this report, it is already clear that there are three main contributors, namely polycarbonate, silver and the power consumed during production. PCB and SMDs were not taken into account yet in this first part of the LCA study. Surprisingly, silver has a remarkably high environmental impact in comparison to polycarbonate, especially when considering their total weights of 0.2 g and 262 g in an IME part of 294 g. Due to the high impact of silver, terrestrial ecotoxicity and human non-carcinogenic toxicity are almost on par with the global warming potential.

With this now known, we make use of an eco-design for IME that has adaptations to facilitate disassembly and recycling. Disassembly is accomplished in this stage of development by photonic debonding and mechanical dismantling. Photonic debonding allowed the removal of graphic inks from the polycarbonate substrate. The eco-design allowed the removal of the backside filling (epoxy in this early stage, polycarbonate later on) with a high degree of purity. Mechanical disassembly with the eco-design requires less force, has a specific interface at which the device is split and may be suitable for semi-automated disassembly once further developed. The eco-design further potentially allows circular manufacturing of IME parts, as silver and polycarbonate may be recycled with a high degree of purity. Further experiments are planned to prove this.

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4. Abbreviations

Ag	Silver
CO_2	Carbon dioxide
Cu	Copper
EOL	End-of-life
ICA	Isotropic conductive adhesive
IME	In-mould electronics
GWP	Global warming potential
kWh	Kilowatt-hour
LCI	Lifecycle intake
LCD	Liquid crystal display
LCA	Lifecycle assessment
MARAS	Material Recycling and Sustainability BV
PC	Polycarbonate
PCB	Printed circuit board
R2R	Roll-to-roll
RGB	Red/green/blue
S2S	Sheet-to-sheet
SMD	Surface mounted device
UNIVAQ	Università degli Studi dell'Aquila
WALTER	Walter Pack SL

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