Sustronics

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Sustainable and Green Electronics for Circular Economy

Deliverable 4.5

Final description of the e-co2-design framework

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Start date Project	June 1st 2023	**Duration**	36 months
Version	2.0		
Status	Final		
Date of issue	04-03-2026		
Dissemination level	Public		

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Management Summary

Purpose and Scope

This deliverable presents the final description of the Eco²Design process framework developed within the SUSTRONICS project, which aims to enable sustainable and circular electronics. The framework integrates environmental assessment, eco-design, and circular system design in parallel with technological development, ensuring minimization of environmental burdens and maximization of environmental benefits. The document reflects on project activities, including Life Cycle Assessment (LCA), technology and software development, and circular business model (CBM) creation, culminating in a revised process framework for eco-design in electronics.

Methodology and Process

To revise the draft Eco2Design framework created at the beginning of the project, this deliverable reflects on following questions looking back at the results and activities within the SUSTRONICS project:

- How were the LCA results used for both technology development and product design?
- How were Circular Business Models developed and how were LCA results incorporated into the CBM development
- Which methods were used to develop sustainable software?
- How did all those activities facilitate the creation of circular solutions?

A mixed method approach was used: analysing existing deliverables, analysing results - specifically the link between LCA results and the CBMs created, interviewing project experts on technology development, bilateral discussions with project partners, and desktop research for available literature.

Main Findings

- *LCA-driven eco-design:* LCA was integrated into technology development, guiding material selection, product architecture, and end-of-life strategies. For example, separating reusable electronic modules from disposable sensor patches in medical devices reduced environmental impact.
- *Eco-design recommendations:*
    - Production phase is the main environmental hotspot for small, short living electronics; design and circularity are key levers.
    - For large, long-lived devices, use-phase energy dominates; energy management is critical.
    - Modular design enables reuse, repair, and recycling.
    - Substituting silver inks with copper or carbon in printed electronics significantly reduces impacts.
    - Use of bio-based substrates offers limited benefits unless end-of-life treatment is optimized.
- *Circular Business Model (CBM) Development:* CBMs were developed using a structured template and workshops, linking LCA results to circulaR-strategies. Data-driven models (e.g., product-as-a-service, take-back schemes) were explored to facilitate circularity and value creation. For durable products, CBMs focused on modularity, repair, refurbishment, and recycling. For single-use products, CBMs emphasized take-back schemes, recycling partnerships, and data-driven services. Modular product designs can enable new business models (e.g., product-as-a-service, subscription, leasing).
- *Technology and Material Development:* Selection of sustainable materials and technologies was iterative, balancing performance, cost, and environmental impact. Compatibility with existing processes and end-of-life scenarios was essential. Trade-offs were managed through stakeholder engagement and prioritization of requirements.

- *Software Development* followed two approaches: 1 Minimize the environmental footprint of software (energy efficiency, resource use) 2. Maximize the "handprint" (enable circularity, extend device life, reduce waste). Recommendations include modular firmware, efficient algorithms, remote updates, and digital product passports for lifecycle tracking.
- *Data Management:* Centralized data collection and management, including Digital Product Passports (DPPs), can support traceability, LCA, and circularity metrics. Data sharing and governance frameworks were established for collaboration.

Challenges and Lessons Learned

- *Data Gaps:* Early-stage LCA faced challenges due to missing data for new materials and processes.
- *Trade-offs*: Functionality requirements sometimes conflicted with sustainability goals; iterative design and stakeholder engagement helped balance these.
- *Systemic Barriers:* Many sustainability improvements require collaboration beyond individual companies, including recyclers, regulators and standardisation bodies.
- *Standards:* For medical devices, standards regarding cleanliness, hygiene and safety hamper the use of new material solutions (e.g. bio-based or recycled materials) or requires new costly certifications.
- *Recycling Limitations:* Printed electronics are not yet well accommodated in existing recycling streams (e.g. challenges in identification and sorting, no take-back schemes for single use medical electronics, missing biodegradation standards).

Conclusions and Recommendations

The Eco2Design framework demonstrates that integrating LCA and eco-design from the outset enables measurable sustainability improvements in electronics. CBMs and data-driven approaches are essential for scaling circular solutions. Ongoing challenges include data availability, recycling infrastructure, and balancing performance with sustainability. We identified several “calls to action” for different stakeholders:

- *Companies/industry:*
  - Continue developing data standards and DPPs for electronics
  - Institutionalise eco-design and LCA in research and development and product development
  - Invest in recycling technologies and infrastructure for printed electronics
  - Establish take-back schemes for repair, refurbishment, parts harvesting and recycling
  - Foster cross-sector collaboration to build circular ecosystems and address challenges such as data availability and recycling infrastructure
  - Create circular value networks with clear roles, responsibilities, and shared objectives, including governance frameworks and shared data systems
  - Monitor and adapt circular Key Performance Indicators (KPIs) as solutions scale
- *Research:*
  - Conduct further research on recyclability of printed electronics and estimate recycling rates
  - Validate biodegradable solutions for relevant use cases
  - Test of the Eco2Design framework in other sectors
  - Integrate diverse data flows for holistic impact assessment
  - Create LCI data for end-of-life treatment of new materials
- *Policy Makers:*
  - Develop and support standards regarding cleanliness, hygiene, and safety for medical devices, especially when introducing new material solutions such as bio-based or recycled materials
  - Address recycling limitations by establishing take-back schemes and biodegradation standards.

Overall, the SUSTRONICS approach demonstrates how eco-design and CBM integration is feasible, impactful, and necessary for the future of European sustainable electronics. SUSTRONICS' technologies and approaches can support reaching the European climate targets and increase European sovereignty in electronics manufacturing relying on abundant and sustainable materials.

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List of abbreviations

Abbreviation	Meaning
ADP	Abiotic Depletion Potential
AI	Artificial Intelligence
B	Byte
BLE	Bluetooth Low Energy
CBM	Circular Business Model
CE	Circular Economy
CEBM	Circular Economy Business Model
CLD	Causal Loop Diagram
CLP	Classification, Labelling and Packaging
CRM	Customer Relationship Management
DPP	Digital Product Passport
ECG	Electrocardiography
EEG	Electroencephalography
EMS	Environmental Management System
EoL	End of Life
EPD	Environmental Product Declaration
ERP	Enterprise Resource Planning
ESPR	Eco-design for Sustainable Products Regulation
GHG	Greenhouse Gas
GWP	Global Warming Potential
IC	Integrated Circuit
IGTS	Image Guided Therapy System
ISO	International Organization for Standardization
KB	kilobyte
KPI	Key Performance Indicator
kWh	kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LED	Light-Emitting Diode
LoRa	Long Range (wireless communication)
mJ	milliJoule
MSW	Municipal Solid Waste
MW	Medical Waste
NFC	Near Field Communication
OEM	Original Equipment Manufacturer
PC	Polycarbonate
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate

PI	Polyimide
PLA	Polylactic acid
PLM	Product Life-Cycle Management
PMMA	Polymethyl methacrylate
POP	Persistent organic pollutants
PSS	Product-Service System
RAM	Random-Access Memory
RTO	Research and Technology Organization
QMS	Quality Management System
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
sLCA	Social Life Cycle Assessment
SMD	Surface Mount Device
TPU	Thermoplastic Polyurethane
TRL	Technology Readiness Level
WEEE	Waste Electrical and Electronic Equipment
WP	Work Package
ZIF	Zero Insertion Force

1. Introduction

1.1. Purpose of the document

The purpose of this document is to develop a consistent, collaborative framework for environmental assessment, eco-design and circular system design (Eco2Design) in parallel with technological developments to ensure minimization of environmental burdens and maximization of environmental benefits. A first version of the Eco2Design process framework was developed at the beginning of the project (Sánchez et al., 2023). Now, the activities during the project on LCA, eco-design, technology development, software development and business model development were reflected to revise that first version. Section 1.3 introduces the key concepts Circular Economy, Circular Design, Circular Business Models, Life-Cycle-Assessments, Circular Data and Circular Ecosystem as a background for the Eco2Design framework. Chapter 2 reflects on following questions looking back at the results and activities within the SUSTRONICS project.

- How were the LCA results used for both technology development and product design?
- How were Circular Business Models (CBM) developed and how were LCA results incorporated into the CBM development
- Which methods were used to develop sustainable software?
- How did all those activities facilitate the creation of circular solutions?

A mixed method approach was used: analysing existing deliverables, analysing results - specifically the link between LCA results and the CBMs created, interviewing project experts on technology development, bilateral discussions with project partners, and desktop research for available literature.

By summarizing the activities, analysing the interdependencies and using literature we created an Eco2Design process framework (chapter 3) with five interrelated and parallel strands of development:

1) Circular Business Model Development,
2) Value Network Creation,
3) Environmental Assessment,
4) Technology and Product Development, and
5) Data collection and Management,

separated into five phases:

1) State of the art analysis,
2) Concept definition,
3) Circular Product-Service-System development,
4) Piloting circular solution, and
5) Validation, adaption and scaling.

In chapter 4, we discuss and conclude our findings.

1.2. Related documents

D1.4 Sustainable materials and their characteristics

D1.5 Sustainable processes and their characteristics

D2.7 Report on software functionalities

D3.2 Gen 1 prototypes, including characterisation and updates to system specification and design for Gen 2

D3.3 Gen 2 prototypes, including characterisation and updates to system specification and design for Gen 3

D4.1 Guideline, framework and KPIs to LCI management and Circular Business Models

D4.2 Analysis of life cycle-based environmental impacts and end-of-life processes of sustainable materials in electronics

D4.3 Digital product passport concept definition

D4.4 End-of-life concepts and new processes for sustainable electronics

D5.3 Initial exploitation, stakeholder engagement, and standardisation strategy

1.3. Key concepts

This section introduces key concepts relevant as background for the document:

- Circular Economy (section 1.3.1),
- Circular Design and eco-design (section 1.3.2),
- Life-Cycle-Assessments (section 1.3.3),
- Circular Business Models (section 1.3.4),
- Circular Data and the Digital Product Passport (section 1.3.5), and
- Circular Ecosystems (section 1.3.6).

1.3.1. Circular Economy

Circular Economy (CE) oriented business and Circular Business Models (CBM) aim to circulate products and materials in two separate cycles, the technical and biological cycles (see Figure 1) (Lüdeke-Freund et al., 2019). “The circular economy is based on three principles, driven by design:

- eliminate waste and pollution,
- circulate products and materials (at their highest value), and
- regenerate nature

underpinned by a transition to renewable energy and materials“ (EllenMcArthur, 2025). In the technical cycle, products are reused, repaired, remanufactured, and recycled (the so-called R-strategies, see Figure 2). In the biological cycle, biodegradable materials are returned to the earth through processes like composting (see Figure 1).

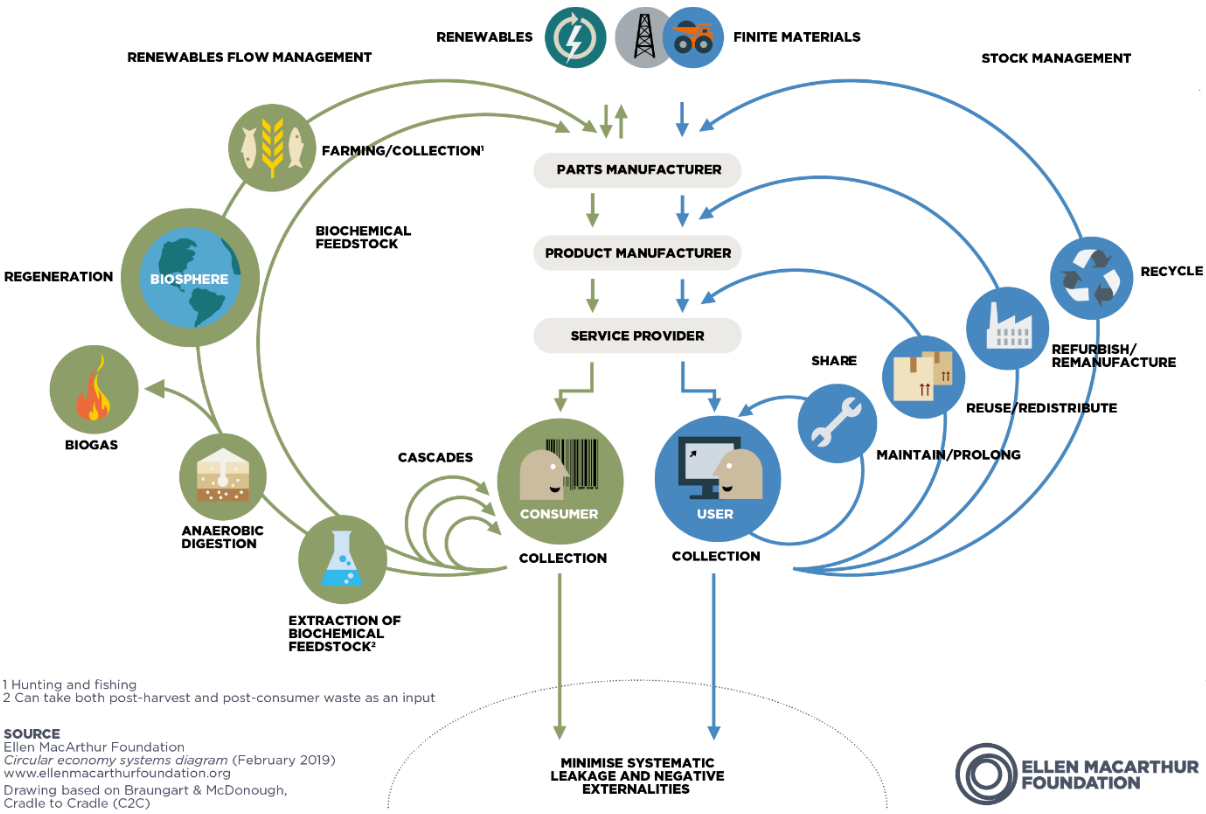


Figure 1: Circular Economy System Design Diagram (source Ellen McArthur Foundation)

Circular economy ↑ Increasing circularity ↓ *Linear economy*

	Strategies	
Smarter product use and manu-facture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consu-ming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of mate-rials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 2: The 9R Framework (Kirchherr et al., 2017)

1.3.2. Circular Design and eco-design

To enable the R-strategies, the product has to be designed accordingly and respective business models and services need to be developed and operationalized (i.e. it does not make sense to create a product that is for example repairable if the respective infrastructure, information, partners, spare parts and services are not available and the repair is not economically viable and desirable). Circular Design intents to (ISO, 2024):

- enable product durability and long-time use;
- enable product and resource recovery;
- minimize resource use and waste;
- create performance-based solutions;
- prevent the use or release of harmful substances;
- minimize environmental impacts along the full product life-cycle;
- explore new relationships with customers, suppliers and partners.

Circular Design includes the design of new value creation models, the design for systems for supporting circular resource flows and the design of closed loops and multiple life cycles (ISO, 2024). That means, that Circular Design goes far beyond the actual product design towards designing and creating circular systems. Therefore, Circular Design includes other design methods and disciplines such as service design, user experience, behavioural design, business design or system design combined with life cycle thinking and eco-design methods such as life-cycle-assessments. Whereas eco-design focuses on minimizing the environmental impact of products by considering their entire life cycle (materials, energy use, end-of-life), Circular Design aims to create closed-loop systems.

The Circular Economy also requires a change in how we buy, use, and divest products. It is often implicitly assumed that people like to buy sustainable products, share, maintain and repair products. However, those practices are bound to behaviours and routines and must be made possible by society like collection schemes or availability of knowledge and materials. Behaviours are complex and hard to change because they are linked to many internal factors (e.g. beliefs, attitudes, knowledge, capabilities, habits, role) and external factors (like norms, relationships, infrastructure, technologies, rules & regulations). Thus, user research becomes especially important because circular products still need to fit to the needs of the end-users. Thus, it becomes critical to identify those needs to increase user acceptance (e.g. change in aesthetics due to bio-based or recycled materials), create a convenient user experience with a circular solution and “direct” the user to change their behaviour towards circular practices.

1.3.3. Life-Cycle-Assessment

Life Cycle Assessment (LCA) is a method for the modelling and estimation of the environmental impacts of a given product or service. The core principles of LCA are, amongst others, the following (ISO 14040):

- Life cycle perspective. LCAs usually (but not always), consider all life cycle stages of a product or service: from raw material extraction, acquisition, conversion to a product, use and final disposal (including recycling). Through such a comprehensive lens, potential environmental trade-offs can be identified.
- Environmental focus. LCA originally focuses on environmental aspects. Currently adapted methods like social life cycle assessment (sLCA) and life cycle costing (LCC) exist to account for the broader sustainability concept.
- Relative approach. LCA is a relative method which centres around a functional unit i.e. a reference function over time that serves as the definition of the product or service under study.
- Iterative approach. LCA is composed of several phases and not only they feed into each other but also require reconsideration of previous phases in an iterative manner.

As per the ISO standards 14040 and 14044, the following phases can be defined in an LCA:

- Goal and scope definition. In this conception phase the research questions to be answered by the LCA are defined. Setting the goals of the study and the expected audience for the results will serve as reference for many decision-making moments during the process. In this phase the functional unit and the system boundaries are also defined. The system boundaries define which processes along the full life cycle of the system are to be included in the analysis. Finally, the impact categories to be studied will be selected.
- Life Cycle Inventory Analysis. In this phase all the relevant data needed for the analysis is gathered and checked for consistency and plausibility. The selection of the relevant data, relevant sources and needed granularity will be set by the goals, system boundaries and indicators defined in the first phase.
- Life Cycle Impact Assessment. Once the full inventory is compiled; the next steps are characterization, normalization, and weighting. In the characterization step, the list of relevant inputs gathered during the inventory phase are converted into environmental impacts using the so-called life cycle assessment methodologies. These are scientifically based models that relate exchanges between the techno sphere and the environment with different environmental effects such as global warming, acidification, etc. This step is mandatory. The normalization and weighting steps are optional, and they allow for the grouping of all environmental indicators into a single score, which allows for easy comparison between systems.
- Interpretation. The interpretation step comprises the analysis of the LCA results. Typically, this involves a contribution analysis and a sensitivity analysis. The contribution analysis involves checking which elements in the life cycle inventory contribute the most to the different indicators. This allows for identification of the main drivers of the environmental impacts of a product. The sensitivity analysis aims to quantify the effect of the variation of key parameters in the results. Finally, and as an option, many LCAs also include scenario analysis, where alternative models using different assumptions for relevant elements are explored, to estimate how alternative versions of the system under study would perform environmentally (e.g. the effect of using renewable energy in manufacturing as opposed to the regular grid).

LCA is mostly used both for internal and external purposes. Internally it allows for identification of environmental hotspots and informs eco-design improvements. Externally, LCA allows the communication and sharing of environmental data both to clients and the public.

1.3.4. Circular Business Models

Circular Business Models (CBMs) can support the prolongation of the product live through maintenance, repair and re-use, or the recycling of the components and materials in the technical and biological cycles. This supports the overarching goal to reduce environmental impacts of our economic activities through the holistic management of integrated resources on a system level (Velenturf et al., 2019). CBMs are an evolution of traditional business models, focusing on characteristics and objectives that emphasize sustainability and the extension of product life cycles (Lüdeke-Freund et al., 2019; Rosa et al., 2019). CBMs include concepts, principles, or goals cantered on sustainable circular economy development. They integrate sustainability and circular innovation into their value propositions, value creation and delivery processes, and methods of value capture (N. M. P. Bocken et al., 2016; Geissdoerfer et al., 2018; J. L. Nußholz, 2018). CBMs are designed to create closed loops for materials and energy, promoting different practices like recycling, extending the product lifetime, intensifying usage, and dematerializing (using less material) within an organization's systems (N. M. P. Bocken et al., 2016; Geissdoerfer et al., 2018). In addition, CBMs provide frameworks to understand and manage complex organizational interactions while promoting sustainability and resource efficiency (Geissdoerfer et al., 2018). These models outline the elements of value proposition, creation, and capture, which are crucial for strategic analysis, planning, and communication within complex environments (Geissdoerfer et al., 2018).

CBMs are defined in the literature with varying conceptual interpretations (Geissdoerfer et al., 2020) defines a CBM is the rationale of how an organization creates, delivers and captures value with and within closed material loops. (N. M. P. Bocken et al., 2016) describe CBMs as business model strategies aligned with CE principles through slowing, closing, and narrowing resource loops. (J. Nußholz, 2017) defines CBMs as how a firm creates, captures, and delivers value through resource-efficient practices that extend the useful life of products and parts while closing material loops. These definitions reflect ongoing attempts to align business model thinking with CE principles. The distinctions lie in how value creation, delivery, and capture are connected to closed material loops, product lifespan extension, and enhanced resource efficiency.

The International Organization for Standardization (ISO), defines a CBM as an

> *“organization’s chosen system of interconnected and interdependent decisions and activities that determines how it creates, delivers and captures value” to “maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development”* (ISO, 2024).

In addition, CBMs provide frameworks to understand and manage complex organizational interactions while promoting sustainability and resource efficiency (Geissdoerfer et al., 2018). These models outline the elements of value proposition, creation, and capture, which are crucial for planning, and communication within complex environments (Geissdoerfer et al., 2018).

Several conceptual frameworks have been developed to support the design and analysis of CBMs by incorporating circular value creation and sustainability considerations. Table 1 presents an overview of these frameworks.

Table 1: Different conceptual frameworks for CBMs.

Name	Description	Reference
Circular business model mapping tool	A visual mapping tool combining value logic and the Business Model Canvas, introducing the element “offer,” and applying a matrix structure to analyze business model elements across different product life-cycle stages.	(J. L. Nußholz, 2018)
Framework for Sustainable Circular Business Model Innovation	An elements-based framework adapted from the Business Model Canvas that extends stakeholder-related components, integrates reverse logistics, and introduces elements for sustainability impacts, benefits, and evaluation.	(Maria Antikainen & Katri Valkokari, 2016)
Circular Business Model Canvas (CBMC)	A modified Business Model Canvas introducing circular-specific elements such as take-back systems and adoption factors, defining new relationships between elements, and providing predefined options for circular value propositions.	(Lewandowski, 2016)
Adapted sustainable business model canvas	A sustainability-oriented adaptation grounded in value logic, restructuring the value proposition into profit, people, and planet, and reorganizing several business model elements.	(N.M.P. Bocken et al., 2018)

In CE literature CBMs have been defined based on the value dimensions and strategies with which they extend product lifetimes (N. M. P. Bocken et al., 2016; Kirchherr et al., 2017). Typical circular business model strategies are shown in Table 2.

Table 2: Business model innovations to slow and close resource loops (N. M. P. Bocken, 2020)

Business Model Strategies	Definition
Business model strategies for slowing loops	
Access and performance model	Providing the capability or services to satisfy user needs without needing to own physical products
Extending product value	Exploiting residual value of products from manufacture to consumers, and then back to manufacturing or collection of products between distinct business entities
Classic long-life model	Business models focused on delivering long-product life, supported by design for durability and repair for instance
Encourage sufficiency	Solutions that actively seek to reduce end-user consumption through principles such as durability, upgradability, service, warrantees and reparability and a non-consumerist approach to marketing and sales (e.g. no sales commissions)
Business model strategies for closing loops	
Extending resource value	Exploiting the residual value of resources: collection and sourcing of otherwise wasted materials or resources to turn these into new forms of value
Industrial Symbiosis	A process-orientated solution, concerned with using residual outputs from one process as feedstock for another process, which benefits from geographical proximity of businesses

1.3.5. Circular Data and the Digital Product Passport

The lack of reliable information about products and the materials means that used products are regularly subject to misjudgements regarding quality, usability, and accessibility. As a result, new goods, raw materials, or the individual purchase of a product are (wrongly) preferred. Reliable information and stable communication and cooperation relationships are therefore a key prerequisite for efficient resource allocation (Piétron et al., 2022). Thus, one important topic to enable the CE is the creation, management, and exchange of data by and to stakeholders along the value chain under the conditions of data security and safeguarding IP. Typical data required by different stakeholder are shown in Table 3.

Table 3: Key information requirements for electronics (Wagner et al., 2023; Wagner et al., 2024)

Information Category	Information
Product Identification	• Model Number • Serial Number • Retail information (product name, type, category, brand) • Date of manufacturing
Company identification	Information related to the manufacturer, such as its unique operator identifier / web domain name.
Material Information	• Information on different materials and location of dangerous substances and mixtures (WEEE) • Hazardous substances (REACH, POP & CLP regulation, Eco-design regulation, WEEE regulation) • Material Composition • Recycled content
Functional and technical specification	• User manual • Instruction for safe use • Specification of product functions
Product design and service information	• Repair information e.g. for disassembly and diagnosis • Resale options • Service availability for take-back for repair or recycling

	• Warranty time
Usage and repair information	• Usage data (purchase date, use cycles, etc.) • Repair data (date, exchanged parts, costs, images)
Certifications and label	Product certifications
Durability /Repairability	• Spare parts availability • Lifetime • Repair information e.g. for disassembly and diagnosis

One respective tool to enable the data management for the CE is the so-called Digital Product Passport (DPP), which use and scope the EU regulates in the Eco-design for Sustainable Products Regulation (ESPR) and the respective delegated acts for different product categories. Aim of the DPP is to:

- enable the digitization and sharing of product information, supporting informed stakeholder decisions;
- improving resource efficiency, and promoting circularity through product longevity, reuse, recycling, and waste reduction;
- allow consumers to access product lifecycle information to compare products and producers.

The DPP assigns a digital identity – including data, history, and other relevant information – to items, enabling traceability throughout each item's lifecycle. The DPP provides standardized and verifiable information regarding a product's origin, material composition, environmental performance, and the manufacturing and recycling processes. In addition, DPPs facilitate transparency by collecting data relevant to sustainability, traceability, and regulatory compliance. The DPP is a digital record that documents a product's lifecycle from raw material to end-of-life, containing product-related data. It is linked to a unique identifier, accessible electronically through a physical data carrier integrated into the product (Isohanni et al., 2025).

1.3.6. Circular Ecosystems

The Circular Economy requires a systemic approach rather than looking at individual companies considering interconnections capacity (cooperation), geographical proximity and the alignment of goals of different stakeholders. A circular ecosystem is a collaborative network of heterogeneous, interdependent actors (e.g., companies, public institutions, NGOs, consumers) that jointly pursue a circular value proposition - such as resource efficiency, waste minimization, and product longevity - by aligning activities across the entire product life cycle (Konietzko et al., 2024; Trevisan et al., 2022). In order to realize this one needs to move away from creating individual business models leading often to suboptimal outcome for the whole system (due to competition between actors) towards creating (new) flows of values across the whole system that incentivizes actors towards cooperation within an overall systems-level function (SI Network, 2020). Circular ecosystems operate through decentralized, non-hierarchical governance structures that facilitate coordination, trust, and information-sharing among diverse actors. Collaboration in a circular ecosystem requires often shared infrastructure, for example an information exchange platform or shared facilities (e.g. for logistics, material recycling, energy production). Besides assets, knowledge and skills can also be shared. Main elements of a circular ecosystem are (see Figure 3):

- **Actors** with diverse complementary capabilities; interests need to be aligned, and trust build up between the actors
- **Governance system**: Governance is both formal (contracts, standards, digital platforms) and informal (non-hierarchical and collaborative) and is often orchestrated by a central actor or a group (the "orchestrator" or "platform leader") who aligns interests, coordinates activities, and manages interdependencies (Adner, 2017; Konietzko et al., 2024). Following elements are of importance (ISO, 2024):
    - Roles and responsibilities of members
    - Structure of governing board

  - Shared objectives and strategies
  - Principles and rules
  - Communication channels
  - Transparent decision-making process
  - Reporting process
- **Circular activities and strategies** like the co-design of products, the establishment of reverse logistic systems, the collaboration in business model and process innovation, or the creation of shared data platforms should provide economic and environmental gains.
- **Data:** To maximize circulation, data needs to be collected and managed within the ecosystem to assess, track & manage (material, financial and information) flows

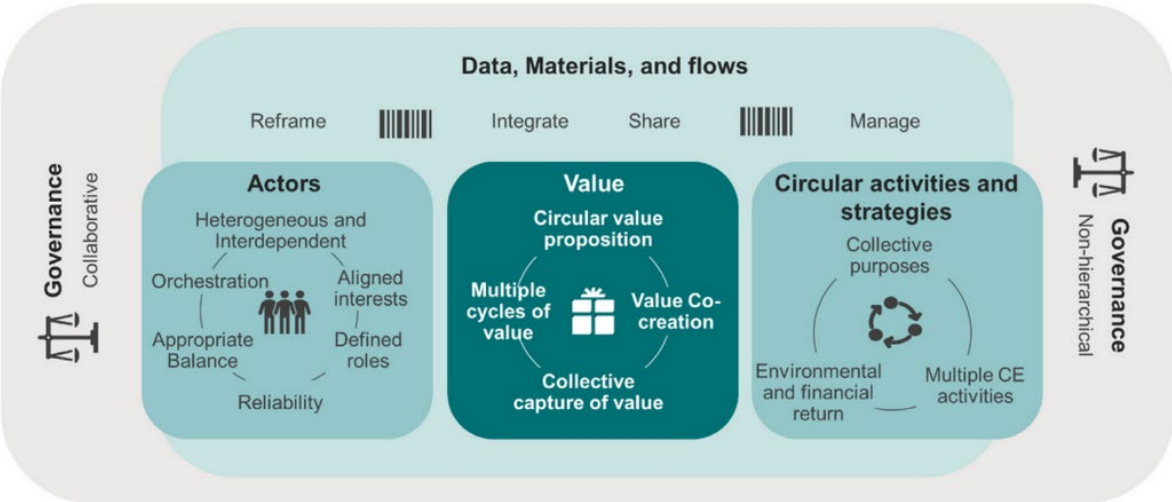


Figure 3: Circular Ecosystem Framework (Trevisan et al., 2022)

2. Methodology and Data

In this chapter relevant processes and activities are analysed for the revision of the Eco2Design Process Framework drafted at the beginning of the project in D4.1 ((Sánchez et al., 2023), see section 2.1). Section 2.2 describes key LCA results for the pilot products (up to Gen 2) and in section 2.3 those are summarized into eco-design recommendations. Section 2.4 is summarizing sustainability aspects and key insights for software, data transfer, computing, and data storage from Deliverable 2.7 “Report on software functionalities” (Soliman et al., 2025). Section 2.5 describes the process of creating the Circular Business Models for the pilot products. Section 2.6 summarizes insights from research undertaken within SUSTRONICS by Tampere University, how incorporating LCA results into the CBM development facilitates the creation of circular solutions in the health technology sector. In section 2.7 the RTO TNO reflected on how they incorporated LCA into the selection and development of more sustainable materials, technologies and pilot products. In section 2.8 it is analysed how the LCA results is reflected in the respective pilots’ business models. All those insights were reflected into the revised Eco3Desing process framework in chapter 3 (p. 39).

2.1. Description of draft and executed Eco2Design Process

The SUSTRONICS Eco2Design process is based on a framework for integrating environmental sustainability into technological development (see Figure 4) that was drafted in the beginning of the project (Sánchez et al., 2023)

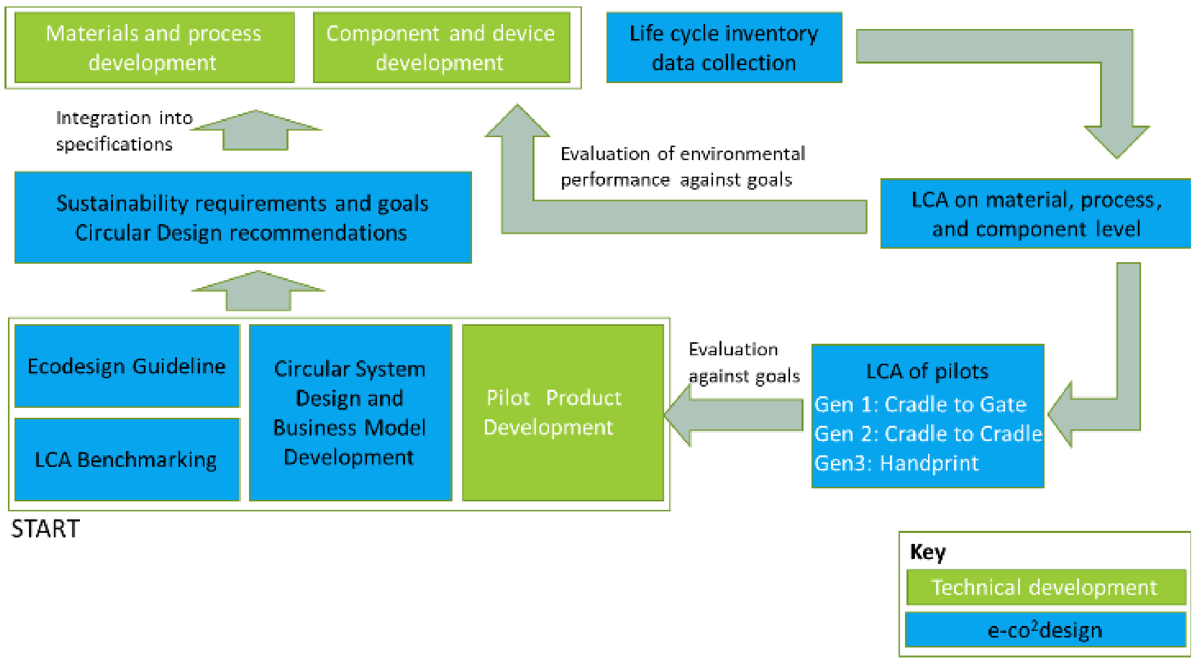


Figure 4: The preliminary Eco2Design process framework (Sánchez et al., 2023)

The pilot development requires that the development team has a mutual understanding of the product’s sustainability requirements and planned technologies. The process that the pilots followed includes three development phases:

- **Gen 1:** Hardware integration with state-of-the-art materials and components for benchmarking performance of required product functionality.
- **Gen 2:** Lab-scale integration with more sustainable materials to validate performance with a sustainable approach.
- **Gen 3:** System integration of hardware and software with developed sustainable materials and components.

In the early phases of the product development, Life-cycle Inventory (LCI) data of new processes and materials is often unavailable. Thus, a first eco-design guideline for printed and flexible electronics was created based on literature to guide the Gen 1 development. To track sustainability progress, a benchmark LCA for each pilot was executed. Following options for the benchmark were identified:

- **Current product:** Using the current product as a benchmark for comparison.
- **Gen 1 of the pilot:** Setting the first generation as the benchmark for improvement.
- **Hypothetical product:** Creating a dummy LCA model using state-of-the-art technologies.

LCI data was collected based on the benchmark selected. Environmental hot spots were identified based on a cradle-to-gate LCA of the benchmark. Strategies for improving Gen 2 products were developed together with the researchers and engineers working on the pilot products.

Based on all the results, the eco-design guideline was updated. To summarize the insights of the different LCAs, we created tables to collect main environmental impacts along the life cycle per pilot and the LCA practitioners deduced first improvement strategies based on the results (see Figure 5). Those were discussed with the project partners to identify concrete eco-design measures for Gen 2 of the pilots. All insights were clustered to derive general eco-design recommendations and those were added to the already existing eco-design guideline

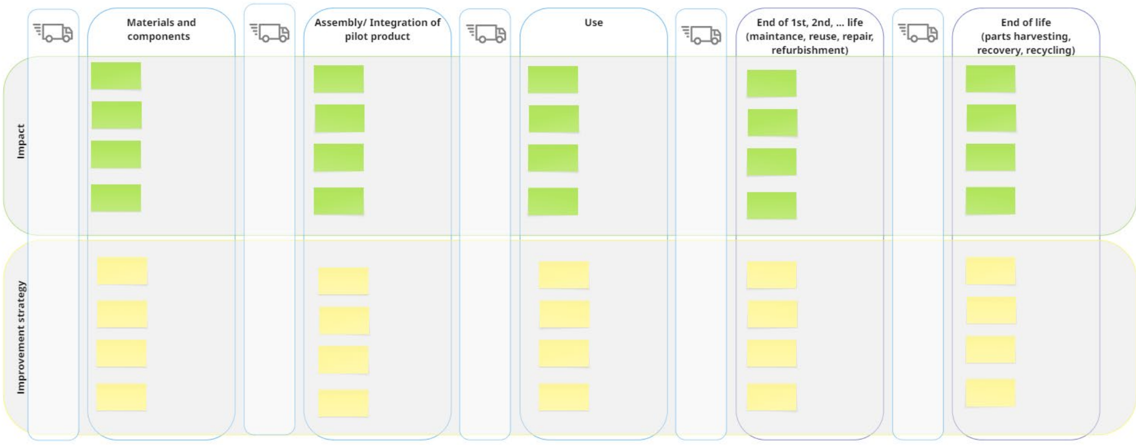


Figure 5: Table to collect LCA insights per pilot

For the generation of LCAs on the Gen 2, primary data (elementary flows) of the new processes and materials were collected. Scenarios for the use and end-of-life phase were developed to create a cradle-to-cradle LCA of Gen 2 pilots. The handprint methodology will be applied for Gen 3. The environmental handprint is an LCA-based metric that describes the potential positive environmental impacts of activities achieved by replacing a baseline solution with a new solution (Tiina Pajula et al.). The process for this has not yet started at the time of writing this paper.

2.2. Key LCA results and eco-design measures

We present the LCA results dividing the pilots into two groups

Group 1 Durable electronics

- Pilot 1.1 Guided Image Therapy System
- Pilot 1.2 Grooming Device
- Pilot 1.3 Lighting
- Pilot 2.3 Automotive

Group 2 Single use electronics

- Pilot 2.1 EEG monitoring
- Pilot 2.2 Wearable health monitoring
- Pilot 3.1a Urine test
- Pilot 3.1b Glucose sensor
- Pilot 3.2 Smart hygiene
- Pilot 3.3 Smart wound care

2.2.1. Durable electronics

Pilot 1.1 Image Guided Therapy System (IGTS)

Energy consumption during use is a major contributor the environmental footprint (44% for Climate Change) of the IGTS. Depending on the “benchmark scenario” up to 11.300 kWh can be saved per year using a full eco-mode (including tube standby). The main contributor on the “material” side is steel (60% of weight, 22% contribution to climate change), aluminium (17% weight contribution and 35% to climate change and the PCBs (2% of weight contribution and 25% to climate change). Besides, a new lightweight and modular geometry could reduce the environmental impact by 8% compared to the current design through reducing the product weight and the amount of packaging material required.

Pilot 1.2 Grooming device

The main contributors to the global warming potential of the benchmark analysis are the Integrated Circuit and the printed wiring board, specifically the electricity mix in manufacturing (62%), the metals gold and copper and the heat used. The sourcing of more sustainable components (e.g. with recycled silver and copper), the use of renewable energies in the production of the components, and the PCB assembly (soldering) were the main levers that were identified to reduce the GHG impact. Using alternative substrates such as PET to replace FR4 PCBs together with printing reduced the environmental footprint. Further potential lies in the refurbishment of the device after first use.

Pilot 1.3 Lighting luminaire

Pilot 1.3 focuses on lowering the environmental footprint of a lighting system combining environmental manufacturing and modular design. During the development of the prototype different options for the electronics layouts and housing designs have been compared using LCA tools and looking at various indicators like GWP, ecotoxicity or ADP. Using a conventional lighting system as a reference, the improvements can be tracked and by covering several indicators, potential environmental trade-offs can be identified.

The results show that the use phase is the main source of environmental impacts due to the longevity of the luminaire and due to the related costs of the energy consumptions optimizing energy efficiency is part of the core business. In SUSTRONICS however, the eco-design focus has been laid on the design and production phases.

Regarding manufacturing, conventional LED strips have been replaced by printed versions manufactured additively. Furthermore, aluminium housing is being substituted by biopolymer housing (which is also used for the substrate), lowering production impacts and simplifying the design. Furthermore, a modular design allows for easy separation of the electronics and housing. This allows for easy disassembly both for repair during use (potentially extending product life) and for End-of-Life disassembly, enabling better material separation.

The material and design selection analysis for the mechanical elements (e.g. housing, diffusor) is still ongoing. The LED strip using printed silver ink has been chosen as it as it provides significant environmental improvements over the conventional PCBA. Life Cycle Analysis showed that copper inks are an even better alternative in the future.

Pilot 2.3 Sustainable Dashboard

The LED, the PC substrates, the electricity used, and the silver ink are the main contributors to the global warming potential. One eco-design measure was to test the replacement of the PC film with different alternatives. The use of only one of the three materials (bio-PC) was technical feasible. It will be also tested whether the same material can be used for injection moulding. If the material can be used for both the film and the injection moulding, the carbon footprint (cradle to gate) of the dashboard could be reduced by up to 28%.

2.2.2. Single-use electronics

Pilot 2.1 EEG Monitoring

The LCA of Gen 2 focused on the climate impacts of electrodes full life cycle, considering different end of life (EoL) options. From the proposed EoL options, all of which are theoretical, the most credits are achieved through re-melting of metal parts e.g., snap buttons, and re-pulping of paper or “classical” WEEE treatment, where metals and plastics are recycled. The highest impacts (CO2 eq) are created when the electrodes would be incinerated as hazardous waste. The main contribution with regards to the global warming potential comes from the battery and the foil bag manufacturing (the aluminium layer of the bag).

Pilot 2.2 ECG and bioimpedance monitoring

Like pilot 2.1, the LCA of Gen 2 for pilot 2.2 focused on the climate impacts of electrodes full life cycle, considering different EoL options. As both systems consisted of similar electrodes made from the same materials, the overarching conclusions are the same. The highest climate impacts (CO2 eq) are created when the electrodes would be incinerated as hazardous waste and potentially lowest EoL impacts would come from recycling. The main contribution with regards to the global warming potential of electrodes manufacturing and use comes from the battery and the foil bag manufacturing (the aluminium layer of the bag).

Pilot 3.1a Urine test

Pilot 3.1a focused on the eco-design and development of a printed electronic sensing platform, where Life Cycle Assessment (LCA) results were systematically used to guide material and architectural choices to reduce CO_2 emissions, resource depletion, and end-of-life (EoL) impacts.

Early LCA screening identified conductive materials, noble metals, and packaged microelectronics as the main controllable environmental hotspots, due to critical raw materials (CRM) extraction, energy-intensive mining processes, and complex manufacturing steps. Therefore, several targeted design transitions were implemented. First, the conductive tracks were redesigned to enable a transition from silver-based inks to copper-based formulations, significantly reducing impacts related to silver mining, smelting, and CRM depletion. Copper offers a lower global warming potential and better availability, while maintaining adequate electrical performance for the application.

In the same perspective, gold-based electrodes were replaced by carbon-based electrodes, leading to a strong reduction in resource depletion and improved EoL scenarios. Carbon electrodes avoid the use of precious metals and are more compatible with low-impact disposal routes, including incineration and material recovery.

The LCA also highlighted the substrate and functional layer stack as relevant contributors. The feasibility of substituting nitrocellulose-based lateral flow substrates with cellulose-based filtering paper was therefore investigated and demonstrated. This substitution enables a renewable, bio-based material with lower embodied carbon, improved biodegradability, and reduced chemical processing, contributing positively to both climate impact and end-of-life performance.

From an electronics perspective, the system architecture was redesigned to replace a fully packaged IC with a bare-die implementation. This change reduces material use (notably epoxy resins, lead frames, and plastic packages), lowers manufacturing energy demand, and improves recyclability by simplifying the material composition of the electronic module.

Finally, the energy storage component was redesigned by integrating a water-based, biodegradable supercapacitor. Compared to conventional Li-ion batteries or standard supercapacitors, this solution avoids critical metals, flammable organic electrolytes, and complex recycling processes, while enabling safer disposal and a significantly lower environmental footprint. The use of aqueous electrolytes and bio-compatible materials represents a major step towards fully sustainable printed electronic systems.

Overall, Pilot 3.1a demonstrates how LCA-driven design decisions can effectively steer material selection, system architecture, and energy storage choices, leading to measurable reductions in CO_2 emissions, CRM dependency, and end-of-life impacts without compromising system functionality.

Pilot 3.1b Glucose Sensor

From early on, existing knowledge of the environmental aspects of electronics motivated a simplified and modular design where most of the electronics were kept as a separate reusable module. As for the expendable skin patch part, LCA was implemented since Gen 1. The first generation's LCA results identified the silver ink in the electrodes and electrical connections of the device as the main driver of the environmental impacts. Gen 2 explored the possibility of substituting the silver conductive ink with alternatives like copper and graphite ink. Finally, Gen 3 removed the need for the electrical connections completely by implementing visual detection of sweat, significantly reducing the environmental impact. Furthermore, recycled PMMA (polymethyl methacrylate) is employed in the housing of the patch, minimising the environmental impact related to the bulk material and incentivizing secondary material use.

Pilot 3.2 Smart Hygiene

The LCA has been part of the development process since Gen 1. The first iteration of the LCA revealed the silver conductive ink and the on-substrate electronics to be the main drivers of the environmental impacts. By extending the scope to include the use phase, the scale of the effects of the prototype's disposability was made apparent. These results motivated a significant redesign which pursued increased modularity by placing as many electronic components as possible in a separate module not in contact with the skin and thus reusable. This two-piece option showed significant environmental impact reductions as opposed to the initial single piece version.

For Gen 2, two variations of the design were compared, which varied in their connection between the disposable and the reusable modules. One version employed a physical connection while the other used an NFC chip to wirelessly connect the label and the transmitter. By virtue of avoiding the use of a chip in the disposable section, the physical connection showed advantages on some indicators like GWP while the avoidance of using gold-plated ZIF connectors proved to yield better results for indicators like abiotic resource depletion (ADPe) in the wireless version. Alternatives to silver paste (e.g. copper-based inks) were tried for the label as well but unfortunately, they did not provide the conductivity, printability and reliability results of silver.

Moving on to Gen 3, improved and miniaturised versions of the prototype will be developed, and the final sustainability of the prototype will be checked.

General overview of LCA results for pilots 3.1a, 3.1b and 3.2

An overview of the full life cycle emissions for use case 3 pilots can be seen in Figure 6 below.

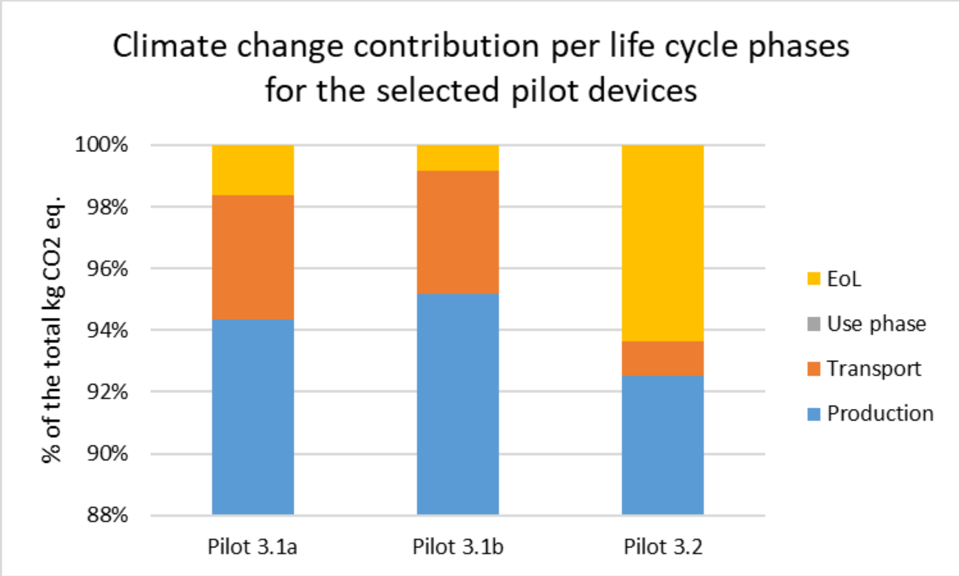


Figure 6: Overview of the emissions distribution alongside the life cycle (source: FhG)

The three pilots (3.1a, 3.1b and 3.2) developed small sized electronic devices with low energy use and short lifetimes, where most of the impacts happen already in the manufacturing stage. Figure 7 below shows a high-level comparison of the production emissions for the pilots. In all cases the electronics are either the main drivers or a significant contributor to the production emissions.

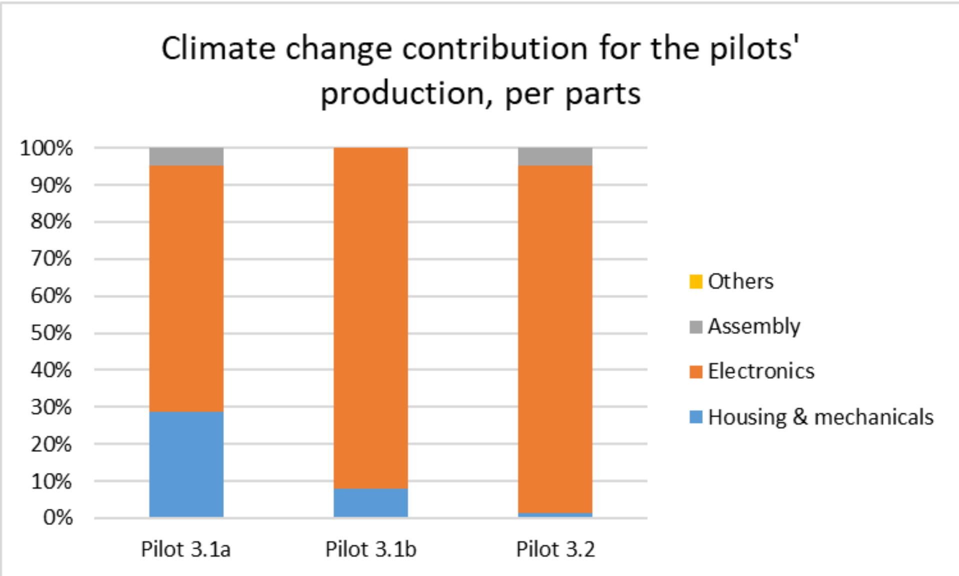


Figure 7: Overview of the production emissions distribution (source: FhG)

Figure 8 below zooms in on the different printed components for all pilots. In all cases the conductive inks printed on top of the substrates show to be a significant contributor, alongside the components mounted on them, in the cases where these are present. In general, the substrates themselves and the printing processes are less relevant (although the latter become more important when moving away from silver inks). The main driver of the impacts for ink manufacturing is the bulk metal needed i.e. silver (Bafana et al., 2018; Slotte & Zevenhoven, 2017) while in the case of the ready-made components the energy necessary for their production is more relevant (Boakes et al., 2023). Depending on the specific architectures of the printed electronic modules, components (e.g. active and passive components, connectors, etc.) may also be added. Such is the case for pilot 3.1a, in which the components can take up to 20% of the production related emissions. Other architectures, however, do not require them or design them in separated (often reusable) modules, as in pilots 3.1b and 3.2 and 3.3.

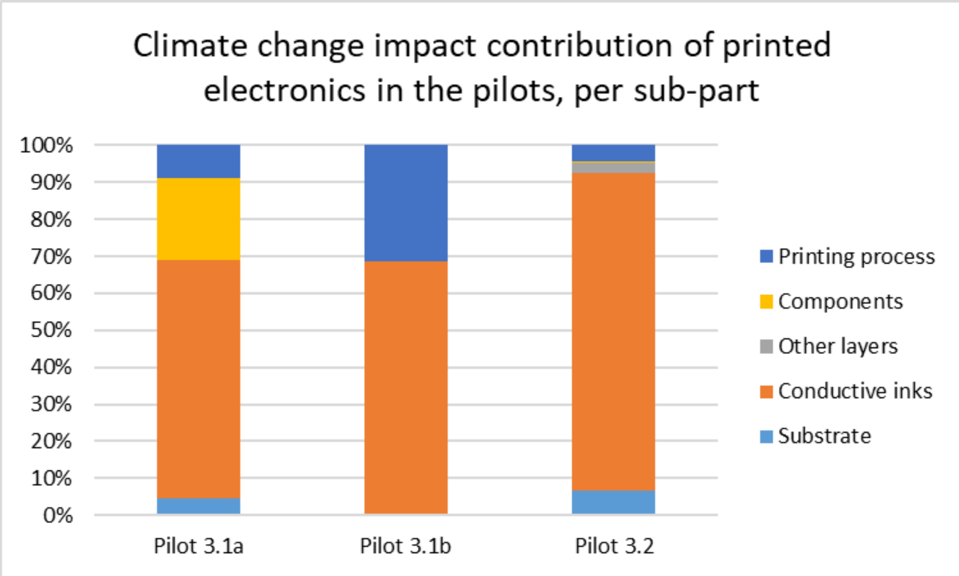


Figure 8: Overview of the printed components' emissions distribution – same size bars side by side (source: FhG)

<u>Pilot 3.3 Smart Wound Care</u>

Pilot 3.3 focused on the eco-design and development of sustainable printed electronics for smart wound care, where Life Cycle Assessment (LCA) was used to compare alternative product architectures and identify the main environmental hotspots across the full treatment pathway. Two Gen 1 design strategies from the eco-2-design framework were assessed: a "Reduce" concept aiming to minimize material use and component count for a single-use device, and a "Reuse" concept based on a modular architecture that separates a single-use sensor patch (including the flexible PCB) from a reusable readout and energy-storage module. When benchmarked against the state of the art (conventional dressings without electronics), both smart-system variants showed a higher product-level footprint, with the Reuse concept initially exhibiting the highest impact due to the added complexity of the reusable module. However, when assessed from a full LCA perspective including the use phase, the smart wound care system delivered substantial savings by enabling longer dressing wear times and reducing overall waste generation and care logistics. In this context, the Reuse strategy achieved the lowest total footprint, as the impacts of the main electronics are amortized over repeated uses. In Gen 2 development the environmental footprint of the Reuse system was further improved.

For the sensor patch, LCA results guided manufacturing and material choices. In a lab-scale evaluation, additive manufacturing of flexible PCBs showed a lower global warming potential (GWP) than conventional subtractive PCB production. The silver ink used in printed conductors remained the dominant hotspot, driven primarily by upstream impacts from silver mining and smelting. Building on these findings, the Gen 2 prototype focused on targeted substitutions to reduce these hotspots, including replacing silver-based inks with carbon-based formulations and substituting PET substrates with paper and partially recycled PET. The results indicated that ink substitution yields a significant carbon footprint reduction, with carbon on paper representing the lowest-impact option among the assessed variants. For subtractive PCB routes, replacing TPU with bio-based TPU similarly delivered a notable reduction in GWP.

Beyond the device itself, the LCA showed that patient-treatment logistics can dominate overall impacts: the transport logistics of health care provider were identified as the hotspot in the use case, even assuming short travel distances (1 km) and the use of an electric vehicle. In comparison, the additional electronics in a reuse system contributed only marginally. Therefore, the design focuses on durability and reliable infection detection to prolong dressing wear periods.

The development demonstrates that selecting the right system architecture can lead to major footprint reductions and stresses the importance of performing a full LCA to capture the impact of the system within its real use case in the design phase.

2.3. Eco-design recommendations based on LCA results

From the LCA results above, following eco-design recommendations can be derived:

General recommendations

- In small electronics devices, the production phase is the environmental hotspot. Therefore, product design and circularity remain the main leverages for improvement of the environmental performance in that phase. However, for devices linked to person-related services (e.g. healthcare professionals), travel-related emissions of that personnel need to be considered, making strategies like reuse and durability to reduce required services particularly impactful
- For larger electronics (IGTS, Luminaire) with a long lifetime (>10 years) the use phase is responsible for most of the GHG emissions. The picture is changing, when renewable energy is used during the use phase.
- Use phase is important also for smaller electronics using batteries as power source if the battery is not re-chargeable (ECG monitoring).
- Energy management during the use phase is specifically important for long-living and energy intensive devices.
- For large mechanical elements low-carbon steel/aluminium or recycled steel/aluminium can reduce the environmental impact.
- Active components such as ICs and LEDs tend to dominate over passive components in energy consumption. Here, re-use and a long lifetime of the parts containing those components make sense. Using bare dies “saves” the emission in backend production. Apart from that, “green sourcing” of components specifically using renewable energies in component manufacturing reduce the environmental impact of those significantly.
- Thus, for single-use devices, reduced energy consumption for production through increased circularity (enable re-use of active components through a modular design, separating “single use” elements for disposal) shows a significant potential for improvement of the environmental footprint. Here, single use elements should be optimized according to their EoL treatment (e.g. in case of waste incineration, avoiding any hazardous materials and/or minimize the carbon emissions).
- For Printed Circuit Board (PCB) design, reducing the number of Surface Mount Device (SMD) components on a PCB and achieving higher levels of integration on the Integrated Circuit (IC) level can decrease the environmental footprint. Minimal number of components also allows integration on less layered PCBs which in turn allows to use more sustainable PCB substrates than standard FR4 with less layers.
- The use of recycled noble metals or the use of copper for any conductive interconnection within the components, interconnection of the components to the tracks and for tracks is beneficial.

Printed Electronics

- Just looking at the PCB without components, substituting an FR4 PCB (subtractive copper etching) with a printed PCB reduces the environmental footprint significantly, moving from silver to recycled silver, copper or graphene inks has a significant effect.

PET with printed silver tracks is only slightly “better” compared to a TPU substrate using subtractive copper etching for the tracks.

- For printed electronics, silver conductive ink is the most critical element from an environmental point of view as it contributes to ADP primarily. Therefore, alternative ink formulations with recycled silver of alternative materials such as copper or carbon based (graphite) inks are of special interest. The specific best choice will depend on the case and the related curing step of the materials during printing as well as the envisioned end-of-life scenarios. Conductance of the printed circuitries and reliability of systems are important performance parameters that suffer when replacing Ag. Depending on the application the alternative conductors might therefore not meet the requirements.
- Optimize track layout to minimize the use of silver inks (or other inks) and optimize overall layout to minimize cut-offs; optimize printing processes to increase yield and minimize waste or number of materials used.
- In the case of subtractive manufacturing technique, recovering the etched Cu parts during manufacturing significantly reduces the environmental impact.
- In general, the choice of the substrate for printing has limited effects on the overall environmental performance. The substrate being a small part of the final product. Biobased substrates (e.g. Bio-PP, bio-PC, bio-TPU, PLA, PEF or paper) can be seen beneficial to global warming potential because the carbon emitted at EoL in case of incineration was sequestrated during plant growth whereas with fossil-based substrates additional carbon is added into the ecosphere. Use of biodegradable substrates is recommended as long as they do not impede the desired functionalities and enable different EoL options for products, like industrial composting.
- The substitution of conventional substrate plastics for bioplastics only shows benefits in terms of emissions if it is not incinerated and EoL. It is also an interesting strategy to reduce fossil resource dependency. Broader environmental benefits could be achieved if the bioplastics were manufactured from rejected feedstock.
- The use of substrates that exhibit some potential for biodegradation can contribute to the reduction of microplastics.
- The use of alternative substrates could enable different End of Life options if materials are applied that can recycled via for instance hydrothermal, chemical processes that fossil-based PET, PI does not allow
- In general, the use of recycled materials for substrates and inks is an interesting alternative for impact reduction (and increased circularity).
- Utilize robust electrical interconnections (prone to fail in flex electronics), designed for device lifespan

<u>End of Life</u>

- For devices with high production impacts, the best EoL strategy is to avoid it: Increasing circularity by repair-friendly design or moving as many electronics as possible out of single-use parts in devices shows the best environmental improvement.
- Designing devices on a modular manner or with less irreversible connections allows for easier separation at EoL which in turn facilitates material recovery by earlier and more efficient separation and increased concentration of valuable materials in the dedicated streams, reducing cross-stream pollution and rejects.
- Simplifying design by reducing the number of materials mixed to support separation process.
- Choose materials with the EoL and dedicated waste stream in mind e.g. biodegradable materials will not biodegrade if used as substrates for printed boards. The environmental benefits of certain materials can be wasted if they end up in the *wrong* waste stream and even contaminate waste streams reducing recyclability of the materials present in this waste stream (textile as example) (Eriksen et al., 2018; Mtibe et al., 2023).

2.4. Sustainability aspects of software, data transfer, computing and storage (D2.6)

The software development process as described in D2.7 followed a decentralized, pilot-oriented approach (Soliman et al., 2025). Each partner was primarily responsible for the design, implementation, and testing of software components according to the requirements of their pilot or hardware subsystem. Coordination occurred within pilot teams and at key integration points, rather than through a centralized development process.

The typical lifecycle for most partners followed these phases:

1) Requirement identification - driven by specific pilot needs and associated hardware designs.
2) Independent implementation - partners developed firmware, AI models, or applications within their own environments and tool chains.
3) Pilot-level integration and validation - software components were evaluated within their respective pilots.

The software development was guided by five core sustainability principles.

1) **Energy efficiency and low power operation:** This principle emphasizes writing efficient code and optimizing algorithms to minimize software energy use while maintaining functionality.
2) **Circularity & Resource Efficiency**: Software is developed to extend hardware lifespan, enable remote updates, and promote material efficiency, supporting a circular economy for electronics.
3) **Sustainable AI:** AI models are made environmentally efficient, governed by strict ethical and privacy standards, and applied to solve environmental and health challenges.
4) **Data Governance & Digital Infrastructure Sustainability:** This principle focuses on designing secure, efficient, and privacy-preserving data systems to reduce the environmental impact of digital infrastructure.
5) **Health & Societal Sustainability:** Software is developed to improve human well-being and societal impact by supporting accessible, preventive, and resource-light healthcare solutions.

These principles provided a framework for design decisions and served as the criteria for categorizing the developed functionalities. For each principle, this section outlines its role in guiding the software development process, and the associated metrics used for validation.

While the project has a general KPI for energy efficiency, the validation approach for each functionality was tailored to its specific domain. However, all partners followed a common methodology:

1) Establishing a baseline by defining a point of comparison, which could be a previous version of the software, a standard industry solution, or a non-optimized implementation.
2) Measuring key metrics by quantifying performance against the relevant sustainability principles during pilot operation or in a controlled testing environment.
3) Documenting impact by reporting on both the functional performance and the sustainability outcomes of the component.

Two sustainability approaches in software development were followed.

1. **Minimizing the environmental footprint** of the software itself or the device the software is running on by
   - Improving energy efficiency by optimising algorithms, using low-power modes, and event-driven data transmission.
   - Adopting resource-efficient firmware and libraries through modular design and efficient sensor data processing.

- Design of sustainable AI by compressing models, optimising inference, and leveraging off-device computing.
- Enhancing storage and digital infrastructure by reducing redundancy, using lightweight data handling, and minimising personal data retention.
- Monitoring performance using KPIs such as power consumption reduction, battery lifetime extension, code size, RAM usage, inference energy per query, and CO2eq from storage use.
- Validating improvements by comparing energy/resource use against baselines and employing tools for measurement and profiling.

2. **Maximization of the handprint** of the software by
    - Promoting circularity and resource efficiency by decoupling hardware-software lifecycles, supporting modular architectures, enabling digital product passports, and digitising workflows.
    - Utilising sustainable AI to facilitate predictive care, generate synthetic data, and enable privacy-preserving inference.
    - Advancing health and societal sustainability by enabling remote monitoring, replacing physical reporting with digital dashboards, and supporting accessible user interfaces.
    - Tracking impact using KPIs including device lifetime extension, increased reuse/recyclability, reduction in physical and paper waste, patient travel reduction, and user satisfaction metrics.
    - Validating outcomes by monitoring field longevity, usage statistics, reduction in waste, and collecting user feedback from pilot deployments.

Table 5 and Table 6 in Appendix A (p. 66) summarize the sustainability recommendations of those two approaches for different software categories and examples of Key Performance Indicators (KPIs) and validation approaches.

2.5. Description of CBM development

Besides doing LCAs, project partners were supported in developing CBMs for the pilot products. A CBM Canvas template was developed and provided to be filled out by the project partners (Abedi et al.). Furthermore, 22 interviews with industry professionals and researchers were conducted and analysed to understand how incorporating LCA results into the CBM development facilitates the creation of circular solutions in the health technology sector (Abedi, F., Seppänen, M., Saari, U.A, 2025).

The standard “CBM Design Template” adapted by Tampere University (TAU) was employed as the conceptual framework for this project. The template builds on the Circular Economy Business Model (CEBM) framework created by (Lüdeke-Freund et al., 2019) and was further developed by the researchers to explicitly structure CBM value dimensions value proposition, value creation, value delivery, and value capture while integrating circular economy design strategies, including cycling, extending, and intensifying. The framework provides a consistent and structured basis for data collection and analysis across the ten pilot cases and supported a systematic examination of how CBMs are conceptualized within the health technology sector.

Prior to SUSTRONICS workshops, the “CBM Design Template” was distributed to project partners to familiarise them with the structure, terminology, and guiding questions. Partners were asked to complete the template based on the product or service under development in their respective pilot cases. This preparatory step supported informed participation and facilitated focused and efficient discussion during the workshops.

Qualitative data were collected using the completed “CBM Design Templates” through a series of focus group workshops with project partners. The template was first applied during two in-person focus group workshops held at the project General Assembly in Munich, Germany, from (28-30, October 2024). Data collection continued through seven online focus group workshops conducted between January and February 2025 using Microsoft Teams. Each workshop lasted approximately 90 minutes and involved between five to ten participants, with an average of seven participants per session.

All workshops were moderated by two researchers and followed the structure of the "CBM Design Template". Discussions focused on clarifying CBM descriptions across pilot cases and examining how circular economy design strategies are reflected within CBM value dimensions. The workshop format enabled open discussion and collective reflection, supporting the refinement and confirmation of CBM descriptions in collaboration with the pilot partners. Figure 9 shows the adapted "CBM Design Template", including the guiding questions used during the workshops.

Tampere University
SustrOnics

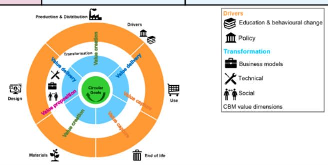
Circular Business Model (CBM) Design Template
Including Guiding Questions

- **Product life time**:________
- **Times of use**:__________
- **Application field**:______________
- **Cost of the product (Approx.)**:__________

Circular Business Model (CBM) Dimensions

Value proposition		Value Delivery		Value Creation		Value Capture	
Products	**Services**	**Target customer & users**	**Value delivery processes**	**Key partners and stakeholders**	**Value creation processes**	**Revenues**	**Cost**
What product features make them sustainable or circular (e.g., design for reuse, recyclability, durability, modularity)? How do they address environmental challenges or customer needs?	What services can be offered to the complement the product lifecycle (e.g., repair, refurbishment)? How can these services enhance/improve the value proposition of the circular product?	Who are the key customer segments that would benefit from circular products and services? What specific needs or challenges are they facing regarding sustainability?	How do you ensure that your products or services are delivered in a way that supports circularity (e.g., through sustainable materials, packaging, distribution)? What steps can be taken to improve the delivery process to reduce waste and ensure products can be easily returned, repaired, or reused? (e.g., localisation of waste management)	Who are the main partners (e.g., suppliers, stakeholders, collaborators, waste management) that help make the circular business model possible? What roles are they required to have to create value in a circular economy?	What processes are crucial for creating value within a circular business model (e.g., remanufacturing, closed-loop supply chain) at your company or organization? How can these processes help to reduce waste and increase resource efficiency?	How can new revenue streams be created through circular models (e.g., product-as-a-service, leasing, or subscription models)? What are the opportunities for capturing value from used/recycled products or materials?	What cost drivers or factors are impacted when transitioning to a circular business model (e.g., initial investment in remanufacturing or other CE strategies)? How can circularity help reduce costs in the long-term vision?

Product life cycle stages:
1. Raw material extraction
2. Processing
3. Design
4. Manufacturing
5. Transportation / Retail
6. Use
7. End of life (EOL)
8. Disposal



Circular economy design strategies

Cycling (C)	Extending (E)	Intensifying (I)
• Refurbishing • Repair • Remanufacturing • Recycling • Reuse • Design for modularity	• Long-lasting products • Upgradability • Timeless design • Marketing and consumer education • Maintenance services • Product support/Customer service	• Rental/Leasing • Product as a service • Digital capabilites developed (e.g. tracking) • Contract management and pricing per unit of service

Figure 9: Adapted CBM Design Template including guiding questions (source: TAU)

Following the workshops, the "CBM Design Templates" completed by the ten pilot projects were analysed using qualitative research methods based on the thematics coding and identification of circular characteristics and features across the CBM value dimensions. This analysis enabled systematic cross-case comparison and supported the identification of generalized CBM archetypes and associated circular economy design strategies. The detailed results derived from the completed CBM Design Templates, including pilot-specific CBM configurations and cross-case patterns, are reported in Deliverable 4.7 i.e., "Review on the design and implementation prototypes of Circular Business Models in SUSTRONICS". The outcomes of the workshops and analytical work have been submitted in a research article which is currently under peer review at a scientific journal. The paper is titled: "Health-Technology Industry Transitioning to the Circular Economy - Development of Circular Business Model Archetypes" (Abedi et al., 2026).

2.6. Incorporating LCA results into CBM development

In this section, we summarized the findings of Abedi et al. (Abedi, F., Seppänen, M., Saari, U.A, 2025) on how incorporating LCA results into the CBM development facilitates the creation of circular solutions in the health technology sector.

The integration of LCA results in CBM development links the environmental performance improvements with relevant circulaR-strategies across all value dimensions, including value creation, delivery, and capture. The causal loop diagram (CLD, Figure 10) of the study conducted by (Abedi, F., Seppänen, M., Saari, U.A, 2025) synthesizes findings from a Gioia-based interview analysis, mapping the interactions between eco-design, technological feasibility, and market aspects. It shows how circular product and eco-design, markets and technological innovation interact through reinforcing and balancing feedback loops.

Environmental hotspots, such as the impact of silver inks in printed electronics, are identified through the LCA. The findings guide the selection of eco-design measures (e.g., material substitution, modular design) that inform circular business strategies for slowing, closing, and narrowing resource loops. These insights support CBM initiatives that incorporate product-service systems (PSS), component reuse, take-back programs, and supplier engagement for recycled inputs, ensuring that sustainability objectives are integrated throughout the CBM.

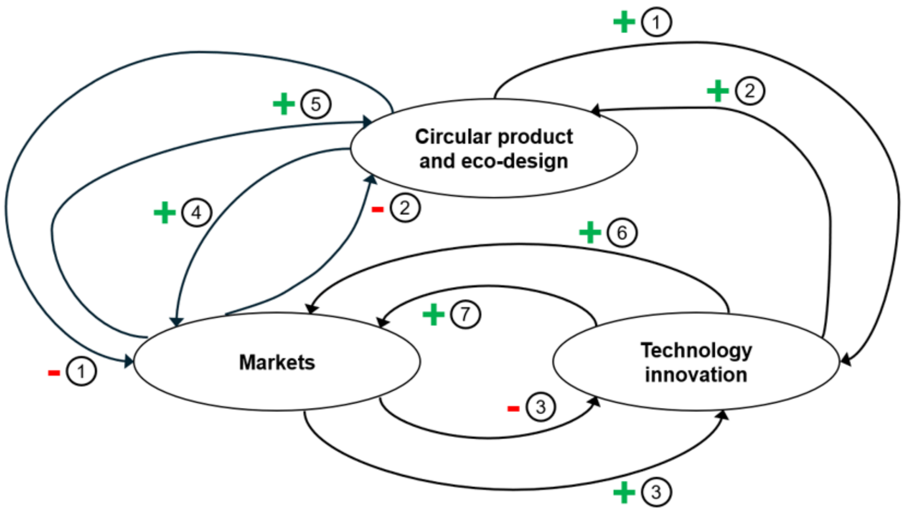


Figure 10: Causal loop diagram of circular product design (Abedi, F., Seppänen, M., Saari, U.A, 2025)

“Reinforcing” loops (+) show that modular design, smart servicing, and service-based models drive technological advancements, enhance product longevity, and strengthen market competitiveness. Eco-design strategies and market driven repairability further promote circularity, while remote servicing and digital innovations improve reliability and efficiency which leads to attracting more customers.

The circular business strategies also motivate LCA transparency and drive LCA data collection, to be able to

- measure environmental benefits,
- identify environmental hot spots,
- guide product design,
- and provide evidence for the circular business strategies, that will again help to improve market acceptance and develop trust among customers.

This is also supported by the data-based product-as-a-service models as they increase data availability for the LCA (e.g. the energy consumption during the use time or number of disposables used). Crucial for successful product development is the industry wide collaboration to create shared data systems (e.g. the Digital Product Passport) and develop, manage and optimize collection, refurbishment, maintenance, and recycling networks.

On the other hand, “Balancing” loops (-) show that functionality requirements limit the adoption of eco-friendly designs, market demand prioritizes performance over sustainability, and cost–functionality trade-offs slow investment in sustainable technologies. Furthermore, for medical devices, standards regarding cleanliness, hygiene and safety hampers the use of new material solutions (e.g. bio-based or recycled materials) or requires new costly certifications. In addition, the recycling of medical waste requires special handling which increases the effort as well as the costs for recycling.

The CLD provides a systems-level view of how LCA results influence not only product-level choices but also the broader CBM framework, enabling iterative refinement of both design and business strategies within the Eco²Design framework.

2.7. Choice of sustainable materials and technologies during the research and development phase

In the following section, the experience of technology providers and developers in SUSTRONICS project for more sustainable solutions and prototypes was reflected by the RTO TNO (Kok, 2025). based on leading questions asked by the main author. The insights are integrated into the Eco²Design Process (chapter 3).

To have more sustainable solutions for products to be implemented successfully, the cost level of products and the performance cannot be compromised. All three aspects are determined by the innovations in materials, manufacturing technology, and product design. The interdependencies between the innovations and key aspects for success are complex and multiple. In the innovations to be developed no choice can be considered as stand-alone (see Figure 11).

Exchanging a material in a product asks for reconfirmed compatibility between materials in adhesion, temperature operations window, mechanical properties etc. Also, for the manufacturing phase the compliance to the technology window (temperature, time, humidity, light etc.) but the technology could also be adjusted to accommodate an alternative material. In case material and technology match, other elements in the life cycle could be also optimised, for instance the eco-design of the product supporting the recyclability of products for the end-of-life phase.

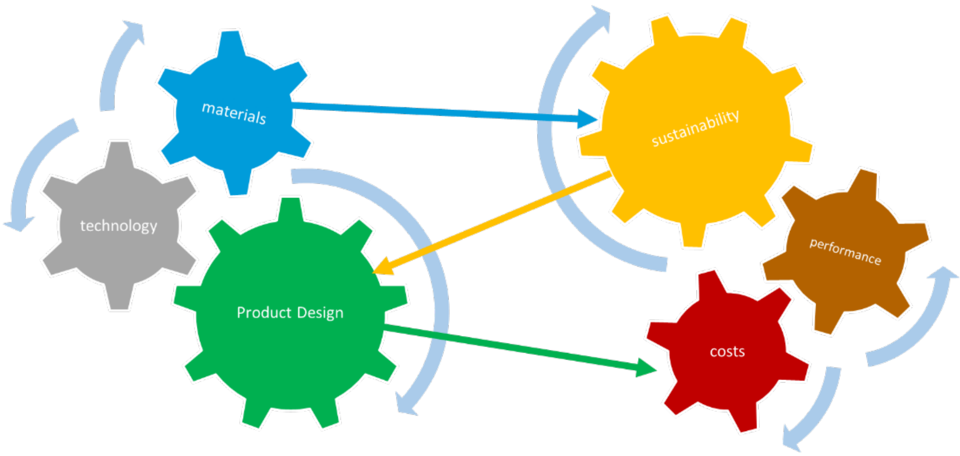


Figure 11: Interdependencies between several factors (source: TNO)

- How did you come from a quite general strategy (e.g. design for repair, environmental reduction) to the concrete solutions (type of materials, processes and overall design & engineering)?
    - In pilots the ambition to create prototypes asked for choices of materials, apply or develop processes and drove the decisions.
- How did you produce the first list of requirements for the pilots? How did you iterate the list – what were the steps from generation to generation?
    - The list of requirements was generated at the start of the project and laid down in D1.1 (Antunes & Rietter, 2023) by the pilot owners and end-users. A distinction must be made between products that have been on the market for longer times like the IGTS and luminaire that have clear requirements for performance, safety etc. and the products under development like the smart wound dressing for which even the functionalities are still under debate. For

the latter category, the requirements were less well defined and merely a wish list that had to be adjusted as the project evolved to a bigger extent.

- What process of interpreting LCA results and choosing alternative technologies materials was followed?
    - In collaboration with sustainability experts generating the LCAs, the options were explored to apply alternative materials of which a reduced environmental impact is to be expected: A distinction was made between:
        1. Identical materials with full or partial recycled content
        2. Identical materials from (partial) biobased sources as alternative to fossil-based sources
        3. New materials with equivalent properties
        4. New materials with different properties
    - First, the availability of materials was researched in addition to developments into new materials. For instance, the PEF material from Avantium is being developed and is not commercially available in films, which could be applied as carrier for electronics. This material which is an example of class three is developed in the SUSTRONICS project to meet the specifications of the "similar properties" requirements. Another example is the PLA material that was available that was researched by VTT and TNO to be converted into films by extrusion and subsequently characterised for compatibility to screen-to-screen printing or roll-to-roll printing.
    - In parallel, LCA analysis quantified the environmental impact of these new materials guiding selection of materials (Hepo-Oja et al., 2024).
    - LCA data was also integrated into the full analysis for the prototypes of the three pilots.
    - For the electronic materials LCA went also alongside the processability and performance studies.

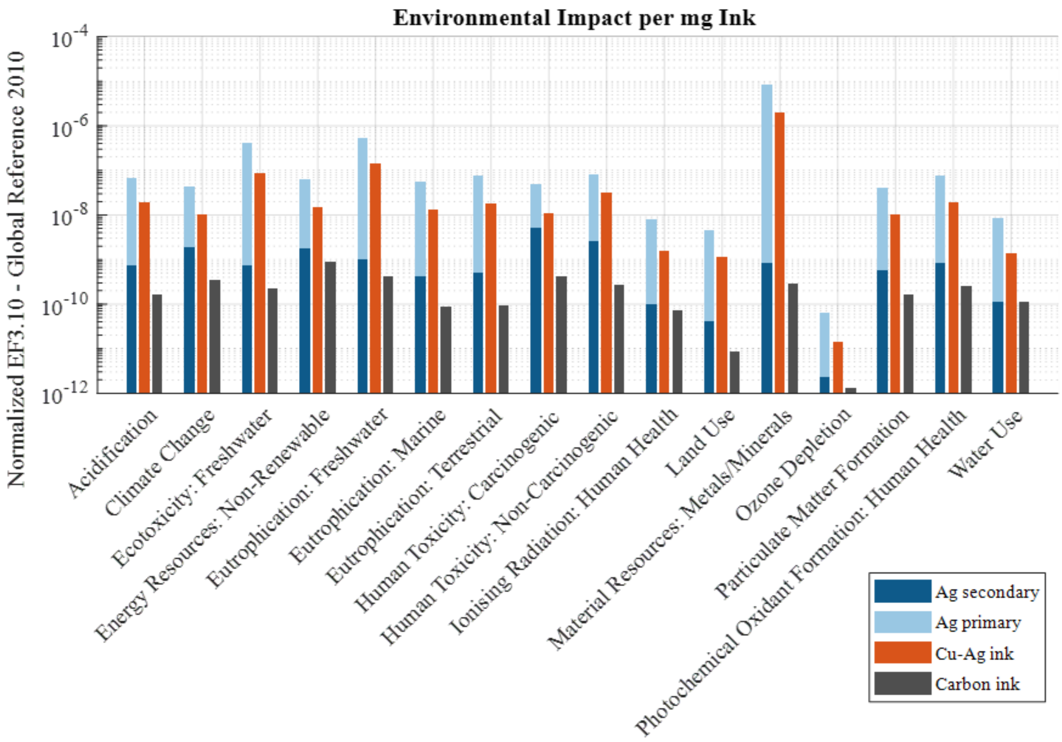


Figure 12: Comparison of the environmental impact of electronic inks across Environmental Footprint categories for printed electronics. (Calculations performed by Infineon based on material data sheets)

- How did you identify environmental hot spots at the beginning of the process.
  - In the pilots that I am involved in, LCAs have been performed even with the known shortcomings for new, to be developed product for which significant data is missing in the databases to be consulted. Another shortcoming is the fact that information about waste streams and impacts are limited, certainly for new products in streams to be adjusted.
- How did you identify alternative processes or technologies based on the LCA insights or other options to reduce the environmental impact compared to the baseline/benchmark LCA?
  - New materials because of different properties could have different instructions for processing that could inspire a choice for an R-strategy. As an example, the PLA that was made compatible with printing and that was known for its 3D printability enabled the mono-material approach of the lighting device (pilot 1.3). Substrate and housing of the same material with only the electronics being a different material. The uniformity in the non-electronic material makes in theory a recycling of both electronic and non-electronic material possible by recycling the PLA by dissolving the PLA and allowing to retrieve the electronics by filtering (hydrothermal recycling processes (Čolnik et al., 2025)).
- How did you prioritize/choose the technology pathway based on those requirements, i.e. the processes and materials you want to work with (e.g. based on certain criteria or pragmatic based on knowledge, experience, and available technologies in the lab)
  - Prioritization was done by the end-user of the pilot ranking requirements as must haves and nice to haves. In this discussion the outlook to materials in the development pipeline that could potentially fulfil the requirements were considered.
- How did the process of choosing technologies and creating technology pathways (different combinations) work?
  - In pilot 3.1, two technology pathways were explored in parallel: subtractive and additive technology which allowed to benchmark the technologies for pros and cons of the list of requirements. An example is the shielding that needs to be installed to prevent the smart wound dressings from interference from the environment. The two technologies provided not the same innovation space.
- What were the decision points when to stop a certain pathway (e.g. after testing material/process)?
  - In the inventory of commercial materials, the performance, costs and sustainability achievements were listed for the intended pilot. If performance was not reachable, material was deselected. For development materials or unknown materials, contact to suppliers resulted in more information, materials samples, or acquisition of materials. For printing of electronics, a benchmark protocol for properties (surface adhesions and energy, mechanical properties, thermal properties, and printing experiments with ranking of results in resolution, conductivity etc. (see D1.4, Immonen et al., 2023).
  - In the realisation of prototypes, electronics were integrated into a housing and if needed combined with existing electronics. In this process, disqualification because of integration challenges occurred if no further solution could be developed.
- How did you choose the materials, technologies, and the design so, that performance and costs are not compromised and the sustainability is increased? How did you work with trade-offs – e.g. higher costs but also more sustainable or more sustainable but less performance?
  - The background knowledge and expertise of partners allowed to for as far as forecast how performance and costs were influenced by alternative materials and technologies. When not known, research needed to be conducted to find out the relationships. For performance, a key insight is that performance is depending on use case and could be a choice of end-user for a certain offering

to the market. As an example, a shorter living wearable could allow smaller battery and less advanced electronics for which costs, performance and sustainability were acceptable whereas a longer living wearable would not be feasible. Cost levels typically are at end-users. For the ambition of the project, sustainability and performance are given priority.

- How did you iterate the list of requirements, and move forward?
    - In WP1, a basic inventory of materials was done collecting a basket of materials from which the pilots could select. Here, sustainability was main priority. For the different pilots, the materials were chosen focussed on performance primarily. The exact balance of priorities in requirements depended on the key features and selling points of the products and are difficult to predict.
- Can you obstruct certain pathways because you just looked at the performance? How can you avoid this?
    - The approach from starting a collection of materials and ranking them for general requirements, like done in WP1, is useful because it saves you first steps if later in the design process of a prototype you would want to change material.
    - The support that a company or organisation could get in setting up this way of working is in exchange of information in literature, from suppliers or in a network of companies or funded (EU-) projects. Competition will work against this.
- Which data is needed to adapt the design?
    - This is dependent on the R-strategy to be followed. If the product is designed to be compatible with the Municipal Solid Waste (MSW) then materials should be chosen to be incinerable and not leave any toxic compounds that can be leached out from landfills or ashes applied in constructions or landfills. If the design is meant for ending up in kitchen and green waste to be industrially composted, the materials should be chosen for this strategy.
    - When aiming to have a refurbishable product, the interconnections in the construction of the product should be designed to be intuitively disconnected, durable for reconnection, meeting requirements for costs and performance of the product.
- What can be still changed in case the product is already manufactured? How can this information be used for the latest version of the product?
    - An example might be to change virgin materials to recycled materials as source. Typically, recycled materials have comparable properties and are easily fitted into the manufacturing scheme of existing products. If the use phase of a product is adjusted, for instance a shorter period which can be adapted by the programming of the part, this should have been made possible in the original product design.
    - Other examples might demand changes in the design of the product that are not trivial, like exchanging parts for different form factors.
    - The design of the product can be done with the ambition in mind to exchange parts of the product in the future. For instance, a different thickness can be incorporated in a construction with spring-loaded connections.

2.8. Linkage between LCA results and circular business strategies

In this section, we analyse how the LCA results have informed the creation of the CBMs, both on the product and the service level, i.e. the value proposition, value delivery, value creation and value capture strategies that the pilot owners stated in the circular business model canvases.

2.8.1. Durable electronics

<u>Pilot 1.1 IGTS</u>

Baseline assessment using LCA of the existing Philips Azurion imaging system showed that environmental impacts arise from energy use during operation (~50%) and from the use of high impact materials. Metals and electronic components are key contributors to the material footprint. Stakeholder analysis revealed that surgeons and hospital administrators face barriers in space, workflow, and cost, while hospitals increasingly prioritize CO_2 reduction, waste minimization, and efficient resource use. That is why it was decided to a) create energy-saving system functionality for IGTS and b) develop a new multi-functional (and upgradable) IGTS relying on a new geometry design that requires less material to build and needs less space and infrastructure in the hospital. At the same time, it can help to reduce the patients' time of stay in the hospital by allowing non-invasive surgery and thus faster healing. This, again, can have a positive sustainability impact, which is currently being investigated.

<u>Pilot 1.2 Grooming Device</u>

The design of the grooming device is on the one hand driven by allowing the product to be repaired and refurbished (replacement of motor, battery and PCBA) and on the other hand reducing the environmental impact of the PCBA. The value capture strategy entails the take back of the product for refurbishment and parts harvesting. For this a reverse supply chain with collection partners like retailers and recyclers needs to be set-up. A subscription model could ease the take back.

<u>Pilot 1.3 Luminaire</u>

Modularity plays a role for the luminaire. Due to the long use-time (>10 years) the focus lays in the overall modularity by design (light module, driver, housing, and diffusor) that again allows for the easy access to priority parts (parts, that are functionally important and are likely to fail or be upgraded). The "circular design" of the housing and mechanicals are motivated by their high environmental impact in the production phase. This parts modularity enables customizability, easy repair, refurbishment, parts harvesting as well as better recyclability. The latter is supported by minimizing the variety of materials used. Energy efficiency, light quality, long-lifetime, minimal maintenance and easy repair are relevant elements of the value proposition. The eco-design related value capture strategies can include: providing light-as-a-service (enabled by low maintenance and repair costs), selling refurbished products, reuse parts and recycled materials. Optimizing energy efficiency in the use phase is of course one of the core goals of the company to minimize energy use and related environmental impacts but within SUSTRONICS the focus lays on the product design.

<u>Pilot 2.3 Automotive</u>

The driver for change comes from the European end-of-life regulation proposal for vehicles focusing on improved circular design and better recycling. The value proposition for the dashboard is the freedom of design, the lightness, robustness and durability combined with a lower environmental impact and use of bio-based materials compared to similar solutions leading to a cost-effective and still highly perceived quality. The design combined with reversible assembly techniques shall allow for upgrading or refurbishing the interiors of vehicles, leading to a prolonged lifetime and additional sales for the part. Revenues can be also created through material recycling depending on the costs of disassembly and recycling of the car and the specific parts.

2.8.2. Single use electronics

<u>Pilot 2.1 and 2.2</u>

For both pilots, the aim is to minimize the environmental footprints of the single use electrodes while keeping the same functionality and same price. Value can be created through take back and recycling and thus lower costs for the recycled materials potentially used in new substrates. The aim is to produce electrodes for product owners with higher sustainability, same performance and if possible, at a lower price. The assumption is that the more environmentally friendly products will also be more appealing to the end-users like hospitals or researchers.

Pilot 3.1a, 3.1b, 3.2 and 3.3

According to the business model canvases, the main value of the medical devices lay in the information generated both for the user, caretaker or medical personnel, leading to better state of health of the user/patient. The purpose of the product is to generate that data. Besides, pilot 3.1a and 3.1b and 3.3 allow for a more convenient and direct diagnosis of the "state of health" at home by the user instead of more tedious and time-consuming doctor visits or other less convenient diagnosis methods. That also reduces the workload in the healthcare system. Pilot 3.2 focuses more on simplifying routines for caretakers by providing the relevant data. For the medical products reliability and accuracy of the data is important indicating the state of health and helping the user to make more informed decisions (e.g. with respect to their diet or changing the wound dressing). Besides, the data can also lead to new scientific insights. Other aspects such as social or self-identity and brand value are less important for those products.

The LCA results have shown that the main environmental impacts for the medical devices come from the production of the electronic components (most of it from the integrated circuits), the conductive inks and the printing process. Those insights suggest designing the pilot products modular into two parts: one part being a more durable and reusable electronic module containing the components with high environmental impacts needed to read out the sensors, including energy supply (battery, supercapacitor) and communication of the data to further IT hardware (e.g. gateways, mobile phones) through NFC or Bluetooth. Given the ability to disinfect the reusable part, it can be re-used for the same user or several users. The other part being the disposable single use sensor patch that will currently end up in the household or medical waste due to hygienic reasons (legally regulated). One crucial part technically is the realization of a reliable and ease to use physical or wireless interconnection between the two parts.

The single use of the sensor patch suggests minimizing its environmental impact, for example, by using alternative ink formulations such as copper or graphite inks, recycled, recyclable or bio-based substrates to reduce fossil fuel depletion as well as optimizing the printing process.

The modularity of the medical pilot products allows for "product as a service" business model strategies such as software application subscription models, leasing of the hardware and selling the single use sensor patch as auxiliary (razor blade model). Those business models lead to closer customer relationships during the lifetime of the product and thus "access" to the product during and after the use time. This allows for take-back schemes, re-use of the product by another user, refurbishment, parts harvesting and eventually recycling of the product. The direct contact to the user (e.g. through the smart-phone application) can also be used to motivate consumers to "behave" eco-consciously; the company can for example provide information and services for taking-back the product to repair, refurbish or recycle the product. One challenge identified is that suppliers might sell less components in case the product is reused, which can be partially compensated by buying higher quality components to build a robust device.

For the disposable single use part, aspects such the choice of sustainable materials or low environmental impact materials are mentioned in the CBM canvases. But also using recyclable materials and enabling recycling (in the mid- to long-term) by setting up recycling partnerships, providing waste collection points (e.g. in pharmacies) and addressing policy makers to overcome current barriers for the recycling of medical waste.

3. Revised Eco2Design Process Framework

Figure 13 below shows an updated proposal for an Eco^{2}Design process framework considering the insights of chapter 2, complemented with additional literature. There are five interrelated and parallel strands of development:

1) Circular Business Model Development
2) Value Network Creation
3) Environmental Assessment
4) Technology and Product Development
5) Data collection and Management

We also separated the framework in five phases:

1) State of the art analysis,
2) Concept definition,
3) Circular Product-Service-System development,
4) Piloting circular solution, and
5) Validation, adaption and scaling.

The boxes in the diagram are representing activities, the arrows the output of an activity the feeds into or is interlinked to another activity. Piloting, validating and scaling the solutions in real markets was not part of the SUSTRONICS project. Thus, the phases 4 and 5 are based on literature and the analysis of the SUSTRONICS exploitation plan D5.5 (Toth & Hakola, 2025). For the phase 1-3 we integrated two case studies the IGTS (pilot 1.1) and the Grooming and Beauty Device (pilot 1.2) interrelating in retrospective the activities during the pilot product development to the Eco^{2}Design process.

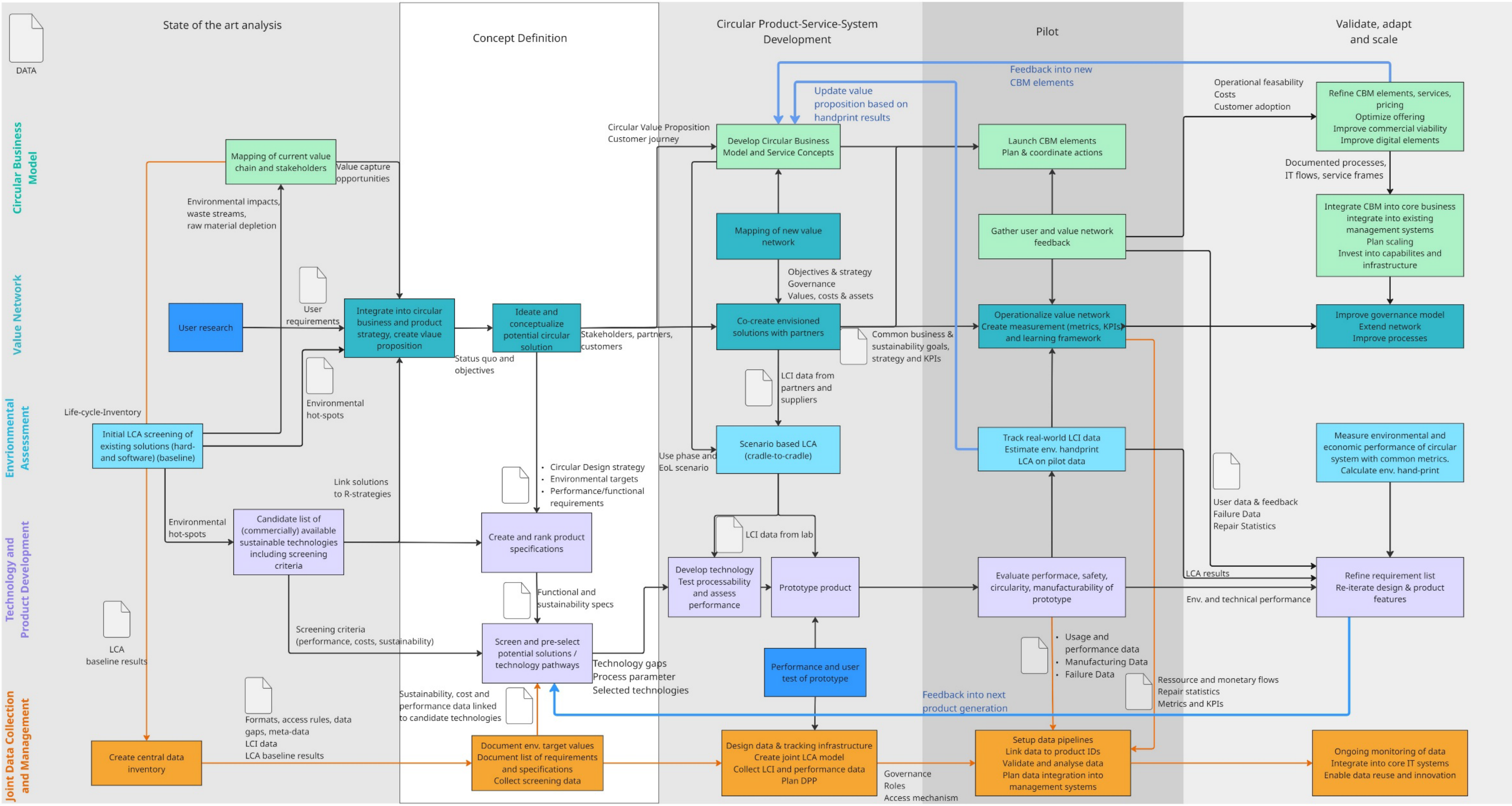


Figure 13: Revised Eco²Design process framework (boxes represent activities, arrows outputs feeding into another activity or interlinkages to another activity, the document icon represents data)

3.1. State of the art analysis

This phase aims to map the current value chain, identify key stakeholders, and assess existing environmental performance through a baseline LCA or similar fast-track analysis. The scope covers both product and business system boundaries, stakeholder relationships, material/data flows, and initial identification of environmental hotspots and uncaptured values. The main result is a clear understanding of systemic impacts and opportunities that sets the foundation for targeted circular interventions.

Circular Business Model and Circular Value Network Development

To create a circular solution based on an innovative technology or redesign an existing linear value chain towards a circular network, start by mapping the current linear value chain of an existing solution.

- Identify all stakeholders directly or indirectly involved in the life cycle.
- Define the system boundary
- Map existing relationships with other organizations and other parties along the value chain, and the associated material flows (materials, components, products), monetary flows and data flows.
- Identify sustainability benefits (value managed) and sustainability impacts (value uncaptured) along the life cycle, and determine who is impacted or benefits from the identified values. Uncaptured values can be values destroyed (negative outcome of current business), missed values (value squandered, inadequately captured or lost), value surplus (redundant value which is larger than required) or value absence (lack of value which is required but has not been created) (N.M.P. Bocken et al., 2015; Yang et al., 2014).
- Identify which of those you can capture, i.e. turn them into value opportunities for different stakeholders in the value chain, including the end-customer. You can also use leading questions available to map the status quo and identify circular opportunities.
- Aim to identify value opportunities with both economic and ecological benefits
- Prioritize opportunities by assessing viability, desirability and feasibility (e.g., required investment, time to cash, required capabilities, internal readiness, strategic fit, market demand, available technologies, and internal and external drivers and barriers) (CIRCO 2025; Ellen MacArthur Foundation 2026a).

The initial mapping is also the basis for mapping out your future circular ecosystem. Figure 14 shows how to create new value based on the distinct types of uncaptured values.

Tools:

- Value Mapping Tool (Bocken et al. 2015)
- Product & Actant journey (Eco-designCircle 2021)
- “Map the value chain and networks of flows” described in ISO 5910 (ISO 59010).
- CirculaR-strategy Scanner (CIRCit Nord, 2020)
- Find Circular Opportunities (Ellen MacArthur Foundation, 2026b)
- Life Cycle Discussion (Eco-design Circle, 2026)

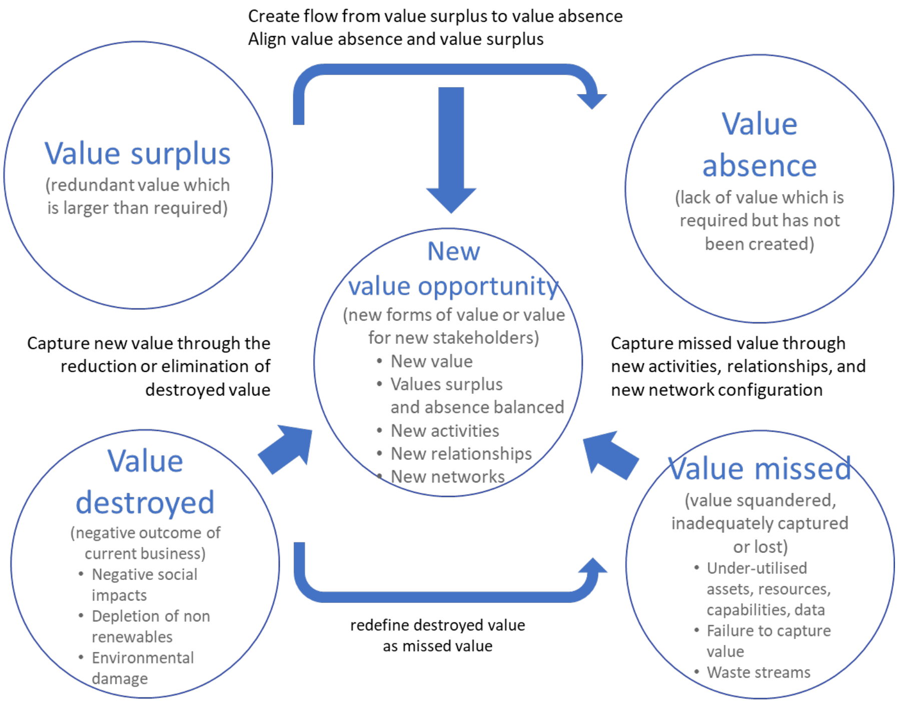


Figure 14: Framework to turn uncaptured values into new value opportunities (source, Fraunhofer IZM based on (N.M.P. Bocken et al., 2015; Yang et al., 2014).

<u>User research</u>

User research is required to understand behaviours and motivations, especially the needs for circularity and the barriers to circular behaviour. Specifically, for the Circular Economy the user research should also go beyond the end-user as the circle of users becomes larger (e.g. purchase staff, first and second user, repair specialists, product-as-a-service providers or recyclers). The user research is also relevant to create a sustainable value proposition (see section 3.2) for the circular solution. Here, any qualitative research method (interview, survey, direct observations, etc.) can be used to gather information about the users' behaviour and needs.

<u>Environmental Assessment</u>

- You can use the stakeholder and value mapping to create the Life Cycle Inventory (LCI), which includes all material and energy inputs and environmental outputs throughout a product's entire life cycle, from raw material extraction to disposal.
- Execute a screening Life Cycle Assessment (LCA), a simplified fast-track LCA, of the current solution as a baseline scenario and to quickly identify major environmental hotspots of the current solution. This exercise helps you to set environmental goals for the new solution and compare your later results to a baseline.
- You can use the results of the screening LCA, together with the information gathered previously (Life-Cycle Inventory), to inform the value mapping exercise.
- In case of software development, establish a baseline by defining a point of comparison, which could be a previous version of the software, a standard industry solution, or a non-optimized implementation (Soliman et al., 2025)
    - Identify metrics and define KPIs to assess software sustainability linked to technology/product sustainability goals and sustainable design principles of software. Useful templates can be found in Appendix B.
    - Measure baseline using key metrics to quantify performance against the relevant sustainability principles

Alternative methods to identify environmental hotspots

- Material (& energy) flow analysis (MFA)
- MECO Matrix (McAloone & Bey, 2009)
- eco-design PILOT (TU Wien, 2025)
- Circular Product & Service Assessment (SustainabilityGuide, 2021)
- Commercial “fast-track” LCA tools

<u>Technology and Product Development</u>

- Use the screening LCA and the value mapping to identify improvement potential on what parts of the lifecycle by what materials and processes or product design could lead to reduction of the environmental impacts.
- Create a *Candidate list:* Identify alternative (commercially) available solutions/technologies from suppliers (market), network of partners or research projects (RTOs as partners) that have a reduced environmental impact
    - List and rate performance, costs, and sustainability of available solutions
    - Identify data gaps in information
    - Check which materials are commercially available now and which are still in development and forecast their benefits to prepare for future evolutions in the field
- Define basic screening criteria and test protocols to characterise materials for compatibility with processing window.
    - Agree on a minimal set of technical and environmental data you need for each candidate (e.g. mechanical and thermal properties, processability, LCA data or proxies).
    - Set up standard lab protocols to compare materials and inks: adhesion, surface energy, mechanical strength, printability, electrical performance, etc.

  This allows you to benchmark new options consistently as they appear.
- Link materials to circulaR-strategies and end-of-life routes.
    - For each candidate material, ask: which R-strategies does this enable?
    - Decide early whether your product should be compatible with municipal solid waste (MSW), medical waste (MW), dedicated recycling of materials like electronics or carriers/housing, industrial composting, etc. This will drive later material choices, product design, and data needs.
- Identify “technology gaps” to specify R&D steps for innovative solutions (materials, processes, functions (e.g. new type of sensor)) that need to be developed.
- In case you develop software for the developed hardware, incorporate the dual perspective, either
    1. aim to minimize the environmental footprint of the software,
    2. maximize the handprint of the software, i.e. enabling the circularity of the hardware or improving other processes to reduce environmental impacts.
- Identify sustainable design principles for software, e.g. energy and resource efficient architecture, modularity, and extensibility (see Table 5 and (Green Software Foundation, 2026; SSTC, 2026)).

<u>Data Collection and Management</u>

- Define data scope and responsibilities (data owner/stewards); typical data points to handle can be seen in Table 4 and DPP Data in Table 3 on p. 17. How to measure and assess circularity is explained in (ISO 59020, 2024)
- Create a simple but structured data model
- Store data in open, interoperable formats
- Collect baseline data and document gaps and quality, capture meta-data

- Create a central inventory or registry (a shared spreadsheet, database, or simple data catalogue that lists all datasets, their IDs, and where they are stored)
- Identify which stakeholder can provide and need which data
- Align with partners on access rules and data aggregation and anonymization, indicate usage rights

Table 4: Example for types of data in the different strands and responsibilities

Strand	Typical data types	Main responsible(s)
LCA & environmental performance	LCI datasets, impact assessment results, hotspot analyses, scenario LCAs	LCA experts, sustainability team
Product & technology development	Material properties, process parameters, test results, failure modes, DPP content	R&D, engineering, quality management
Circular Business Model	Usage data, return/repair statistics, logistics flows, service events, cost data	Business development, service, operations
Value-network	Economic and material flows, partner roles, contracts, data-sharing rules, KPIs, joint targets, data catalogue	Strategy, legal, consortium/ network manager

3.1.1. Case Studies

Pilot 1.1 – Philips IGTS

Philips IGTS applied the Eco2Design methodology during the development of a new imaging concept. The current landscape of image guided procedures in surgical environments shows significant operational and sustainability challenges. Hospitals increasingly aim to reduce environmental impact through lower energy use, waste reduction, and responsible procurement, while technology providers face similar expectations through corporate sustainability commitments.

Baseline assessment using LCA of the existing Philips Azurion imaging system showed that environmental impacts arise from energy use during operation (~50%) and from the use of high impact materials. Metals and electronic components are key contributors to the material footprint (Figure 15).

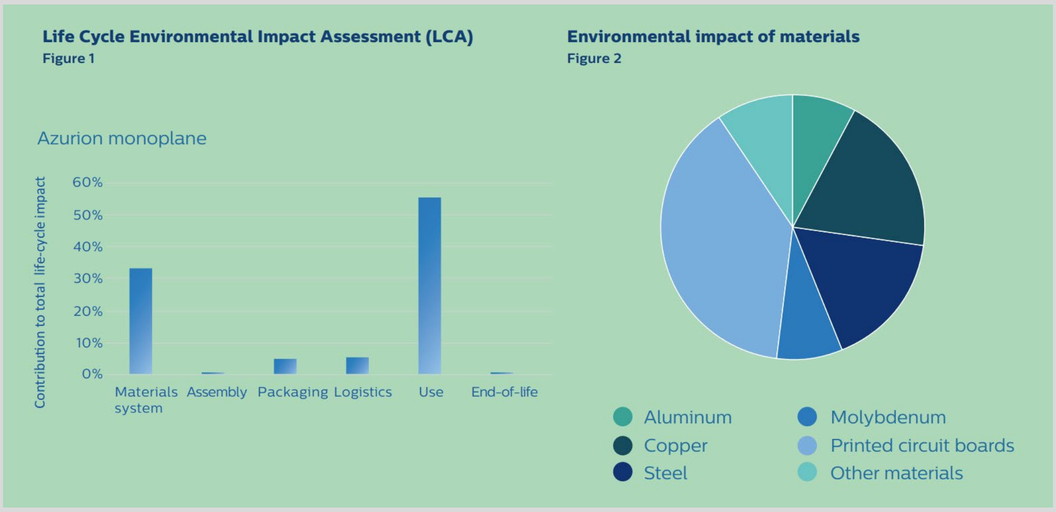


Figure 15: LCA and environmental impact of materials Azurion monoplane. Source: Environmental performance overview - For Azurion image-guided therapy platform, document nr. 452299167511)

Stakeholder analysis revealed that surgeons and hospital administrators face barriers in space, workflow, and cost, while hospitals increasingly prioritize CO_2 reduction, waste minimization, and efficient resource use.

A broader system view was created using a value mapping of material and stakeholder flows in five phases (Figure 16): the initial installation of the solution, the daily procedure steps of preparation, treatment, and recovery of a patient, and the maintenance and decommissioning of the system at end of life. This highlighted that the environmental impact of a procedure is influenced not only by imaging equipment but even more so by downstream effects in the clinical pathway. Shorter hospital stays associated with minimally invasive approaches could reduce overall environmental burdens.

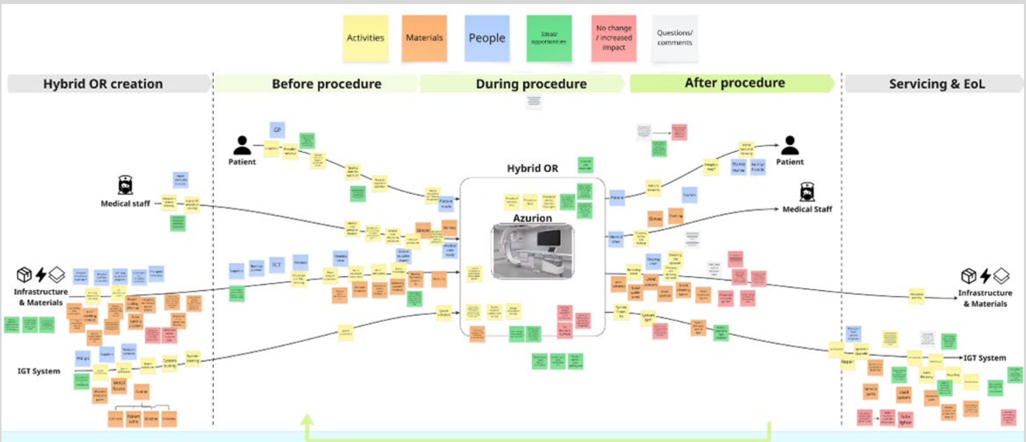


Figure 16: Value mapping of an IGT system in the context of a Hybrid operation room, covering the installation phase, the daily procedures, and the servicing and end of life (EoL) of the system.

This mapping of user needs, environmental hotspots, and systemic impacts provides the basis for defining a revised concept tailored to sustainability and emerging procedure requirements.

Pilot 1.2 – Philips Grooming and Beauty

LCA Baseline and Hot-Spot Analysis

In the state-of-the-art analysis, Philips Grooming & Beauty identified the key business drivers for developing more sustainable PCBAs. Philips has set ambitious company-wide targets for reducing carbon emissions, which have been cascaded down to the Grooming and Beauty business. In addition to internal goals, there is strong external pressure from both regulation and consumers for more sustainable products. A central focus area is the carbon footprint of the devices. Previous LCAs have shown that PCBAs contribute significantly to the total environmental impact of a product, making them a priority topic for the business and for this pilot. For SUSTRONICS, the ambition is to achieve a 30% carbon footprint reduction on the PCBA level, and a 30% reduction for the overall device.

As a next step, environmental Hot-Spots were identified through in-depth LCAs based on the bill of materials. These analyses showed that ICs are the largest contributors to the total carbon footprint, followed by the printed circuit board itself (substrate) including the copper tracks.

3.2. Concept Definition

In this phase, the goal is to define ambitious but achievable environmental targets and specify the most suitable circular business strategies and R-strategies, based on the insights from state-of-the-art analysis. The scope includes articulating a sustainable value proposition (see Figure 17), ranking technical and sustainability requirements, and translating uncaptured value into concrete new opportunities. The main result is a well-founded concept and set of requirements guiding subsequent product, technology, and ecosystem development.

Circular Business Model and Circular Value Network Development

The objective during the concept definition is to set environmental goals and identify the best R-strategy and circular business strategies to reach those.

- Choosing an *R-strategy* should contribute to the environmental goals derived from the LCA baseline scenario. A layered approach can translate the circular value proposition (e.g. providing repairable product together with repair support) into circular design strategies (e.g. design for repair), circular design targets (e.g. specific parts to be replaceable by consumer), and circular design requirements (part A to be replaced in X steps with common tools) (Ville et al., 2024).
- Create a *sustainable value proposition*, i.e. "a promise of the economic, environmental, and social benefits a company delivers to its customers and society through its offering" (Laukkanen & Tura, 2022). The basis for this is to turn uncaptured values into new value opportunities. The value proposition should describe your envisioned circular solution and how this supports your target stakeholders, partners & customers reaching their goals, i.e. which environmental, economic and social value it brings to the ecosystem (DDC, 2021). Also identify data driven value creation opportunities. New required customer behaviours need to be identified and measures how to support those (Ellen MacArthur Foundation, 2025).
- Identify new customer behaviours required (returns, repairs, subscriptions) and how you will support them.
- Design simple, integrated customer journeys addressing sustainable purchase, sustainable use, maintenance, repair and upgrade and sustainable divestment options (for-re-use, refurbishment, parts harvesting and recycling) using existing channels and platforms where possible
- Integrate the results of the state-of-the-art analysis into a *circular business and product strategy* that slows, closes, or narrows material loops throughout the entire end-to-end value chain; summarizing the customer and stakeholder needs, your

strategic company's goals, the chosen circular economy opportunity and the potential solution, metrics how to measure your (environmental, social and economic) impact, partners you need, and a roadmap to create your circular solution. Questions to ask are (Ellen MacArthur Foundation, 2026a):

- "What questions does your team need to explore to move forward?
- Who are the key players and collaborators you need to make this happen?
- What is the early narrative you want to create around your intentions that you can share with others?
- What is working against you? How do you plan to address these challenges?
- What is the early narrative you want to create around your intentions that you can share with others?
- What are the next steps?"

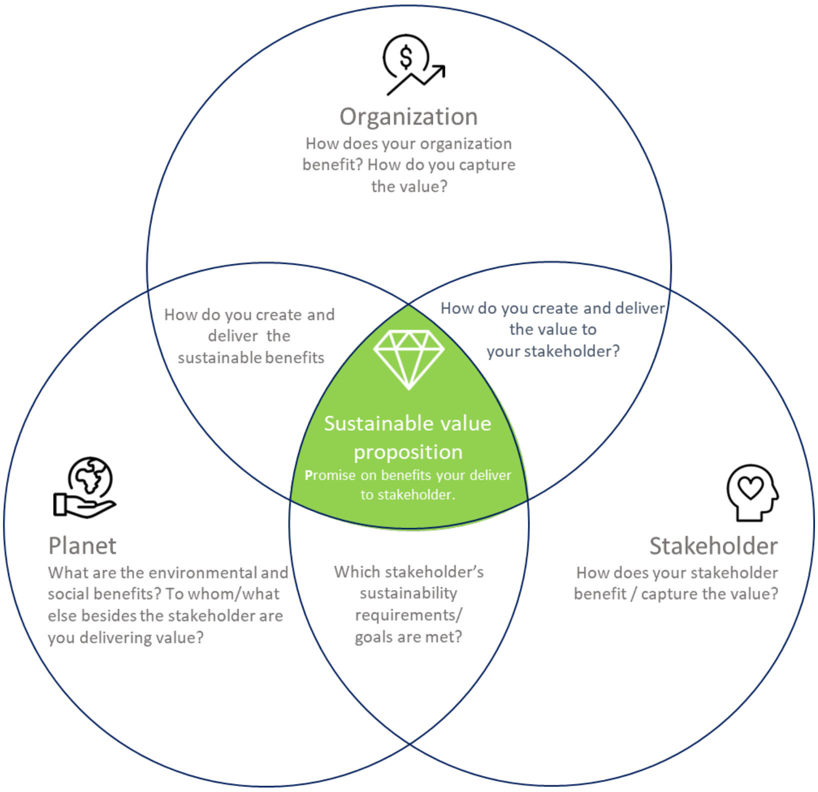


Figure 17: Sustainable Value proposition template (based on (N. Bocken et al., 2013)

<u>Technology and Product Development</u>

The third outcome of the concept definition phase are product and technology requirements and specifications.

- Create a first list of requirements
  - Technical performance and safety
  - Regulatory constraints
  - Cost expectations
  - Software sustainability (e.g. interoperability or data passporting)
  - Environmental targets linked to the LCA (e.g. reduce abiotic depletion potential by 40% or cut fossil carbon footprint in half)
  - Differentiate between
    - Existing products: requirements for performance, safety etc. are (partially) existing and can be well defined
    - New products: less well defined, start with "wish list" and iterate as you learn

    - Rank requirements with customer/user as obligatory or optional
- Choice of alternative technologies (material, components, processes)
    - Choose alternative technologies from the candidate list of available technologies based on best fit to performance, cost, and sustainability requirements
    - Identify how processes (manufacturing processes, assembly) need to adapt to new type of technology (e.g. material) to enable implementation
    - Create different *technology pathways*, e.g. different combinations of potential technologies and/or advancement of a technology towards the defined requirements
- Define clear go – no/go criteria (gate criteria) for each technology pathway. For each path, specify:
    - Minimum performance and reliability.
    - Processability and integration feasibility (e.g. printing on new substrates, bonding to housings).
    - Environmental performance relative to the baseline (LCA).
    - Expected cost range and maturity.
    - Fit with the chosen R-strategy and CBM (e.g. is mono material design feasible? Can materials be separated at end of life?).
- Do not treat any technology choice as stand-alone: check compatibility with other materials and processes ("technology window") and with the envisioned CBM.

Environmental Assessment

- Develop validation
- Collect screening data from suppliers of available technologies (environmental product declarations, carbon footprints or primary LCI data)

Data collection and management

- Identify, which data is needed to enable your circular business model (e.g. certain services), and how to create, collect, store, and analyse it
- Document LCA baseline results, environmental target values or improvement ranges relative to the baseline
- Document requirements and gate criteria
- Create a shared glossary to ensure that everyone uses same definitions
- Collect sustainability and performance data for screening potential technologies
- Store data with clear metadata and links to candidate technology
- Create roles and access mechanism (digital certification)

3.2.1. Case Studies

Pilot 1.1 – Philips IGT-S

Building on the insights from stakeholder needs, environmental hotspot analysis, and the mapping of the current value chain, the concept definition focuses on enabling more sustainable and user-aligned solutions for emerging image-guided procedures.

Overall Design Ambition

The concept aims to address several systemic limitations identified in the state-of-the-art analysis:

- **Space constraints** in crowded OR environments
- **Workflow interruptions** created by existing imaging geometries

- **Material and resource intensity** of current system designs and installations

These findings informed the ambition to explore a solution that is more flexible, modular, and lightweight, and that better supports circular design strategies throughout its lifecycle.

Eco-design & Sustainability Goals

Based on an existing Philips Eco-design framework, environmental goals for the new concept were determined, with the ambitious aim to outperform (definition given by internal Eco-design framework) on sustainability in at least three of the five Eco-design focus areas. It was decided to aim for outperformance with this concept in the areas of Circularity, Packaging and Total Environmental Impact.

These goals build directly on the environmental hotspots identified in section 3.1 and help translate them into actionable design directions.

System and Solution Level Impact Potential

While product level improvements are valuable, the solution's broader environmental potential lies in supporting clinical practices that reduce downstream impacts. Preliminary desk research showed that enabling less invasive and more efficient procedures could contribute to substantial reductions in resource use across the patient care pathway, far outweighing the product-level benefits. A further deep dive will be executed in the final part of the SUSTRONICS project to quantify this benefit of reduced patient hospital stay even further, as part of the scenario based LCAs of the next section.

Pilot 1.2 – Philips Grooming and Beauty

Circular Design Strategies

Based on the business drivers and identified Hot-Spots, the key focus areas and R-strategies were selected and further detailed. The main priority was to reduce carbon impact. "Reduce" is a fundamental strategy because it lowers environmental impact and typically also provides cost and weight benefits. "Repair" is critical to meet Right-to-Repair EU Regulations and consumer expectations; the new PCBA design must not hinder the product architecture in enabling repairability. "Refurbish" is more relevant for high-end products (and therefore less applicable to the device in scope), though it is still considered important to ensure future-proof design and potential future business models (leased devices). Finally, "Recycle" is also included as a strategy to lower environmental impact and guide end-of-life considerations.

For the concept definition phase, the primary focus is on redesigning the PCBA. However, as clarified during the state-of-the-art analysis, the PCBA must enable and support the relevant R-strategies. Therefore, the product-level and process-level aspects are also considered. A high-level description of the concept definition for each level is provided in section 3.3.1

3.3. Circular Product-Service-System Development

This phase focuses on developing the integrated product, service, and business model concepts, selecting and prototyping suitable technologies, and designing collaborative value networks. The scope covers lab-scale realization, technology pathway selection, partner engagement, circular business model development, and validation via scenario-based LCAs. The main result is a functional prototype and circular solution demonstrating improved sustainability, partner collaboration, and circularity aligned with the defined goals.

Circular Business Model and Circular Value Network Development

- Develop a *Circular Business Model* (CBM) based on your concept of the circular solutions (how, see for example (ISO, 2024) or Figure 9, p. 31) – specifically thinking about end of life treatment options, infrastructure and technologies and reverse flows from the start.
  - Think about how data can enable elements of the business model (e.g. services) or enable performance-based business models (e.g. product-as-a-service, pay-per-use, leasing, subscription-based access). Those business models facilitate the feasibility and economic viability of reuse, repair, upgrades, take back, refurbishment, parts harvesting & material recycling and thus the prolonged and circular use of products, components and materials. That again can lead to a reduction of the overall environmental impact of the circular solution.
  - Your CBM should be linked to your core business goals building a broad business case with a strong product-market fit. Also integrate secondary values like brand value or customer loyalty in the business case (Ellen MacArthur Foundation, 2025).
- Educate, engage, coordinate, and collaborate with required stakeholders along the end-to-end value chain to *co-create the envisioned solution*.
  - Map the new circular value network including value flows (and losses).
  - Identify *sustainable values* created for the partners (e.g. more efficient processes, higher quality of recycled materials, or new and better data).
  - Fairly distribute values, costs, required investments and identify shared assets.
  - Create *shared objectives*, a shared circular economy strategy, complementary business models, and joint targets (metrics & KPIs). Circularity key performance indicators are for example defined in (ISO 59020, 2024).
  - Create a *governance framework* (see section 1.3.6, p. 18) for the system (ISO, 2024). This governance framework should also set rules on how to deal with confidential information and how to share and create intellectual property.

Important is to early think about how to scale the business model at a later stage, that is to list which capabilities, processes, partners, and infrastructure is needed to scale the business model (Ellen MacArthur Foundation, 2025).

Technology and Product Development

- Assess available technologies or develop alternatives
  - Order available commercial technologies that meet specifications or
  - develop alternative technologies that meet the specifications and realise technology (in lab). Characterise, test processability and integration and assess performance of realised technology.
  - Explore innovation potential of technologies that goes beyond 1:1 substitution of existing technology and exploit unique properties of new materials to enable circular design (e.g. better process improvements, easier product integration, use of technology (e.g. material) in other parts of the product, better recyclability)
  - Develop software (firmware, AI models, dashboards, mobile applications, data platforms) within a separate environment and toolchain according to requirements.
  - In case of parallel technology pathways, assess pros and cons
- Prioritization

    - Rank solutions according to performance, sustainability, and costs
    - Disqualify technology (pathway) if performance requirements cannot be reached
    - Choose technologies to be integrated into product
- Prototype solutions
  - Build prototypes that integrate electronics, housing, software, and other components, using your selected technology combinations.
  - Where relevant, combine innovative technologies with existing ones to reach a functional system.
    - First iteration: realize function based on available technologies that meet the requirements, if possible, with higher sustainability
    - Second iteration: integrate newly developed technologies
    - Third iteration: Improve sustainability and performance, create best fit
  - Disqualify the development pathway, if the integration of the product components into the overall product architecture is too challenging, leading to increased costs or loss of performance, and no design workaround is found to be feasible.

<u>Environmental Assessment</u>

- Use LCA to assess different technical solutions and design choices (design scenarios) to choose the best fit between performance, costs, and sustainability (using weighted criteria). For new innovative products based on innovative technology the data must be researched from prototypes in lab environment or modelled based on insights previously collected.
    - Validate whether the proposed concepts are environmentally better than the baseline.
    - Assess trade-offs between different designs, e.g. a higher repairability can mean that additional interconnection technologies are required. Those increase the bill of material and might decrease the durability of the devices.
    - Discuss trade-offs with partners (e.g. higher bill of materials vs higher repairability)
    - Validate whether final prototype reaches sustainability targets compared to baseline.
- Validate sustainability of software against baseline using identified metrics and KPIs. Exemplary validation approaches can be found in Table 5 on p. 66.
- Capture design decision and rationale
- Share LCA results among partners to push for the reduction of environmental impacts beyond the boundary of the business model and the product design, for example, by increased use of renewable energies or the use of recycled materials in components.
- Create a joint LCA model for the network
- Develop smart data capture and collection technologies for the required Life-Cycle-Inventory (LCI) data from different partners using the shared data space to store the data (see below)

<u>Data collection and management</u>

A common data space makes sense to share data and access common metrics, targets, and LCI data and LCA results.

- Design data & tracking infrastructure for the required data (technology specs, LCI, product data (see Table 3), sensor data of smart product (e.g. of product or manufacturing line), business data)
- Set up the shared data space and governance
    - Define, which data needs to be captured, stored and analysed (format, meta-data)
    - Who can read/write which data (role-based access).

  - How data is validated and updated (data quality rules, approval workflows).
  - How to handle confidential and IP sensitive information (aggregation, anonymisation, encryption).
- Design a future joint LCI model (expected data fields, update frequency, and data provider)
  - Collect data from partners with standardized template (e.g. Material composition, recycled content, hazardous substances, standard property sets (mechanical, thermal, processability), available EPDs or LCA data (and their scope and quality)
- Plan DPP and tracking of data
  - Which product and usage data should travel with the product (e.g. material composition, repair history, use hours, number of cycles).
  - Which identifiers to use (QR codes, RFID, GS1/EPC, serial numbers)
  - Data schema of DPP, interoperable data standards
- Collect laboratory and prototype data systematically (store test results linked to material batches and process settings)
- Connect data to R-strategies, end-of-life routes and KPIs

3.3.1. Case Studies

Pilot 1.1 – Philips IGT-S

Scenario-based LCA (Concept Level)

Early LCA assessments demonstrate that design interventions in the concept —such as optimized material use, modular system configurations, and improved maintainability—can lead to meaningful reductions in material use (~1200 kg reduction) and environmental impact across manufacturing, logistics, and end of life scenarios (~10% CO_2 reduction). This however also showed the team it was not sufficient yet to meet the ambitious -20% target on total environmental impact. It was identified that extending system lifetime through design for durability and upgradability could further enhance sustainability performance and can potentially reduce total CO_2 impact up to -25%.

In addition to material focused scenarios, energy consumption was explored as an important lever for impact reduction. Several energy saving measures can be integrated into the imaging system design, including low power modes, automated shutdown of components, and standby strategies for displays and other subsystems. These measures were evaluated through multiple usage scenarios to assess their potential contribution to lowering operational energy demand.

By incorporating these energy related improvements into the scenario-based LCA, the analysis could account not only for the effects of material reductions and circular design strategies, but also for operational energy savings across realistic user profiles. This comprehensive approach strengthens the understanding of how system level efficiency measures contribute to reducing the overall environmental footprint of the imaging solution.

The impact reduction of the reduced hospital patient stay will be further explored as part of these scenario-based LCAs.

Circular Business Model Development

As part of the circular PSS development, different business model options were explored to reduce adoption barriers and support long-term sustainable use of the solution. The analysis showed that hospitals face a typical early adopter dilemma: while minimally invasive approaches offer clear benefits, high upfront investments and uncertainties regarding utilization slow adoption.

To address this, three business model directions were considered: conventional purchase, subscription-based access and pay per use. Models where ownership remains with the provider—such as subscription or usage-based models—were identified as particularly supportive of circularity. They enable lifecycle management, upgrades, and eventual recovery or reuse of system components, aligning economic incentives with sustainable resource use. However, these can also increase the financial risk to the provider and do require the systems to be flexible, modular, and reusable.

Pilot 1.2. – Philips Grooming & Beauty

<u>PCBA-Level Technology Development and Re-design</u>

- ICs: For these components, the most promising method to reduce environmental impact is to select—or incentivize—suppliers to use renewable energy in their production processes. Since Philips has no influence over IC design and manufacturing, these components considered out of scope of the SUSTRONICS project.
- Tracks: Additive manufacturing was identified as a highly promising alternative to conventional copper etching, by virtue of printed silver track technology. Consortium partner TNO is actively researching and developing this technology, evaluating its potential to enable more sustainable PCBAs. Printed silver solutions meet the balance of most sustainable objectives whilst importantly also meeting device functional electrical requirements. Therefore, this alternative is selected for further concept development.

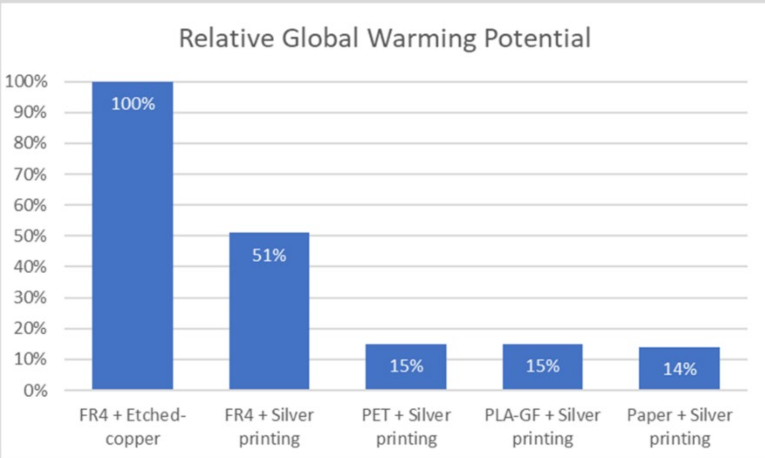


Figure 18: Global Warming potential of different PCB (substrates) and circuit materials (figure made based on data from (Nassajfar et al., 2021))

- Substrate: Potential alternative substrates for the standard FR4 were also investigated within the consortium. A crucial input was the PCBA electronic functional requirements from the Grooming & Beauty business, and along with a list of potential alternative substrates; a Pugh Matrix[1] was generated. After evaluating and scoring together with stakeholders – a final substrate was selected. A driving design principle was to minimize substrate size and thickness.
- Other components: Most remaining electronic components are standard, supplier-designed parts. As with ICs, the use of renewable energy by suppliers is an effective strategy to reduce carbon footprint, and similarly direct influence on

component design is limited, also placing them outside the scope of SUSTRONICS. However, it was later identified that certain resistors could potentially be produced using an alternative, lower-impact manufacturing method that is easily combined with the additive silver track technology. This solution was selected for testing as part of the optimised PCBA concept.

Prototype product development

The PCBA is integrated into an existing appliance, which places limitations on design freedom. The product already includes design requirements for battery replacement and consumer repair, for which established solutions were available. The primary challenge for SUSTRONICS was incorporating the new printed flexible PCBA into the appliance and adapting interfaces to connect with existing modules.

The entire PCBA is designed to be reversibly connected to the device, enabling disassembly and reassembly for repair and potential future refurbishment activities. The reversible design also enables efficient liberation at end-of-life, improving the recyclability of the product.

Circular system development and data management

The focus of the pilot was on redesign with a specific focus on the PCBA itself and not on process design. However, it was considered how the redesign fits in the current process or how the process should be changed. For the R-strategy “Repair” and “Refurbishment,” the existing Philips processes are considered as reference. As add-on to the concept development a QR code will be added to the product referencing the user to the DPP, leveraging knowledge from existing Philips practices and the UpCode workstream.

For the “Recycling” strategy, consortium partner MIREC was consulted to assess the impact of shifting from copper-etched PCBAs to silver-printed electronics. MIREC is a pre-processor which is the first stage of recycling where the batteries are removed from the product, the products are shredded and the materials are sorted in different value streams. These streams are then further processed and recovered by smelters (metals) and compounders (plastics) MIREC indicated that the likelihood of effective recycling would decrease significantly, as their current processes are not designed to detect, sort, or recover this specific type of PCBA. Consequently, it remains uncertain how silver-printed PCBAs would be handled within existing recycling streams.

An alternative approach would be to bypass the pre-processor entirely and collect the PCBAs through a separate route, sending them directly to a dedicated smelter. Small scale trials, at Remondis PMR, showed that a precious metals smelter can recover silver from printed electronics through incineration followed by purification, reaching a recovery efficiency of around 95% – but only if the incoming waste stream consists exclusively of these PCBAs.

The main challenge remains how to obtain such a pure PCBA waste stream. One option would be to ask consumers to disassemble their shaver and send only the PCBA to Philips or directly to PMR. However, this would create significant drawbacks: high transport and packaging impacts, increased costs, and considerable inconvenience for consumers.

Another option would be to have consumers return the complete shaver to a dedicated facility where the PCBAs are manually removed by Philips or a third party. Yet this approach faces the same issues - high transport impact, prohibitive cost, and limited convenience - making it similarly impractical.

If silver-printed electronics become widespread, the most realistic solution is that e-waste processors such as MIREC adapt their sorting processes to recognize and separate these new silver-printed PCBAs. Once separated, the recovered fraction could then be forwarded to specialized silver-recovery processors such as PMR in Moerdijk.

1. A Pugh Matrix is a criteria-based decision matrix which uses criteria scoring to determine which of several potential solutions or alternatives should be selected.

3.4. Piloting Circular Solution

Here, the goal is to test and demonstrate the circular solution under real conditions, verify feasibility and performance, and track environmental impacts by updating LCAs with pilot data. The scope includes monitoring operational, technical, and environmental KPIs; validating business models and circular processes; and capturing pilot usage and lifecycle data. The main results are lessons learned about implementation, updated sustainability performance values, and actionable insights for further refinement

Circular Business Model and Circular Value Network Development

In the piloting phase the different elements of the solution are implemented and actions are coordinated.

- Plan and document processes, roles, IT flows, and services frames to verify how the pilot CBM can be integrated into the core business (Ellen MacArthur Foundation, 2025).
- Test critical assumptions, customer adoptions, and operational feasibility as well as costs of pilots focusing on sustainability and circularity (Baldassarre et al., 2020).
- Create measurement and learning framework to track operational metrics, customer metrics, (technical) performance and environmental indicators (Ellen MacArthur Foundation, 2025).
- Apply necessary environmental certifications, standards, and regulations to enable the CBMs.
- Identify which standards and certifications need to be developed or refined and decide within the value network which partner engages in the relevant organizations.
- Use our environmental handprint results to update your value proposition, i.e. claims how the solution can reduce the environmental impact of other partners, especially of your end-customer, within the value network.

Product and Technology Development

- Evaluate the pilot solution against the mandatory requirements, including the following criteria:
  - Functional performance and safety
  - Durability and reliability
  - Environmental performance (based on updated LCA results using prototype data)
  - Indicative cost and manufacturability of the product
- Test critical circular assumptions wherever possible to verify the feasibility of the solution (e.g. lab-scale recycling of materials or composting trials, disassembly tests).

Environmental Assessment

- Update the LCA with pilot data.
  - Replace initial estimates and assumptions with measured data from pilot production and prototype testing and usage (e.g. actual energy use vs estimates).
  - Verify that environmental goals have been met and finetune the product and system design
  - Quantify handprint
- Estimate the environmental handprint of your solution, the potential positive environmental impacts of your solution compared to the baseline (For example, in health applications, the use of remote hardware to monitor the status of health of

people may increase material use due to the use of the device but then on the other hand they reduce hospital stays and complications for patients. As a result, the materials used during the shorter stays reduce the amount of waste generated per patient. These result in environmental benefits which also often translate into financial savings. The production of less waste per patient and having to stay less time at the hospital support the business case for novel health-tech solutions that apply electronics and have associated health applications.)

- Validate the sustainability of the software based on real world data. If possible, realize automated validation and reporting frameworks within software (e.g.: automated data logs, digital audit trails, dynamic tracking of KPIs, validation plans)

<u>Data collection and management</u>

In this phase data is captured and used to update the LCA calculations for the solution and track the progress of the product development, solution deployment and CBM implementation through the main circular economy and eco-design related (common) KPIs and metrics.

- Implement the data capture procedure for:
  - Product use data (usage time, intensity, location where relevant).
  - Performance data (failures, degradation, sensor readings).
  - Data from the various stages in the circular processes (returns, repairs, refurbishments, recycling outcomes, losses).
  - Resource and monetary flows (materials, energy, water, monetary transactions).
- Use the Digital Product Passport (DPP) data tracking mechanism defined in Phase 3 “Circular Product and Service System Development” to link data to the product IDs.
- Integrate pilot data into the shared database (set-up data pipelines from production systems and partners)
- Validate and analyse the data collected for LCA and from CBM testing rounds (replace assumptions, recalculate impacts, and compare real data to target values, refine the financial model)
- Share insights across the value network (aggregated performance and impact data relevant to the operations)
- Plan the integration of CBM data flows into core systems (ERP, PLM, CRM, QMS/EMS systems).
- Identify data requirements for future certifications, audits, and regulatory reporting.

3.5. Validate, adapt and scale

The objective of this phase is to optimise the solution based on pilot feedback, adapt the value proposition and business model, and plan for large-scale deployment and ongoing improvement. The scope includes institutionalising circular R&D practices, updating KPI tracking systems, refining requirements, and ensuring readiness for scaling across products, regions, or markets. The main result is a robust, validated framework and solution ready for broader adoption, with continuous monitoring and improvement mechanisms in place. The objectives of this phase are to: (1) use the pilot results to optimise the system, (2) plan the scaling of the solution, (3) institutionalise circular R&D practices, (4) reduce the overall environmental footprint of the system further, (5) optimize the offering, (6) revisit the CBM elements and (7) improve the commercial viability through monitoring the individual and common metrics.

<u>Circular Business Model and Circular Value Network Development</u>

The offering can be scaled within the same product, towards a broader consumer group, across the portfolio, or across geographies - in conjunction with adapting the value proposition (ISO, 2024). The (Ellen MacArthur Foundation, 2025) identified typical pitfalls and potential solutions for scaling CBMs summarized in Table 12 in Appendix C on p. 70.

- Use customer and operational feedback to refine the product offering, pricing, user interfaces, logistics, and repair/cleaning processes (Ellen MacArthur Foundation, 2025). Pilot data can also be used to validate and adapt the financial model for the scaling phase, including longer-term value and risk reduction.
- Use usage data, failure data, and repair statistics to feed back into the development of the next product generation to improve the circular design of the product.
- Adapt partnerships, services, and processes in the circular value chain.
- Integrate CBM into the core business processes and practices and brand message.
- Expand the product and related service system in the scaling phase by adding other external elements in it and involving additional stakeholders. Expanding the solution and system can help to mitigate and create new opportunities for improvement (ISO, 2024).
- Invest in capabilities and infrastructure to be able to scale the solutions.
- Integrate new processes and data flows developed for the CBM and required in the implementation into existing management systems like Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Quality and Environmental Management systems.
- Make the use of eco-design and LCA tools and methods mandatory in the R&D and new product development processes.
- Scale manufacturing and supply chain with the help of key partners.
- Strengthen supplier collaboration to support additional services, for example, repair, recycling, and reverse logistics.
- Broaden the scope of KPIs so that they incorporate circular economy targets and adapt incentives and bonuses so that they reflect circular economy values (Ellen MacArthur Foundation, 2025).

Environmental Assessment

For scaling purposes, quantify the full lifecycle and system benefits. In the scaling phase, the pilot LCI/LCA model should be developed into an LCI/LCA **reference model** that is used for ongoing monitoring during the full product lifetime of new products and services:

- The reference model should be updated with real-world data at pre-defined intervals.
- The reference model can by also applied for new products, markets, or user segments as new offerings in the product portfolio are scaled.
- Use updated LCA based on real data to capture the full life-cycle benefits beyond the product itself, especially in use phase and at system level, and in the EOL stage.
- Continuous monitor and optimize software sustainability performance (e.g. energy monitoring)

Technology and Product Development

- Check which technologies and materials are ready to be deployed at industrial scale, considering supply, cost, and certification.
- Feed lessons learnt back into the next generation of products
- Refine requirement lists based on pilot feedback: add missing criteria, adjust thresholds, update must-have vs nice-to-have features and applications.
- Update your material and technology options and selections with what was learned about availability, performance, sustainability, and integration feasibility of previous product versions.

- Improve the test protocols and gate criteria based on what proved predictive in practice.

Data collection and management

- Create and deploy on the organizational and ecosystem level a KPI tracking system for ongoing monitoring (including updates of real-world data at pre-defined intervals).
    - The set of circular economy KPIs applied should reflect the circular and sustainability values in the offering and they should be measurable with quantitative data (e.g. share of recycled content, reparability, and repair costs). They should be validated with qualitative assessments on the impact of the product (e.g. including also avoided negative impact), alongside cost and performance.
    - Add in the KPI tracking system all new products, markets or user segments as new products and solutions are scaled for new markets.
    - Integrate circular economy KPI data on the into the core IT systems of organizations (ERP, PLM, CRM, QMS and EMS)
- Stabilise and maintain the joint LCI/LCA data assessment as a regular monitoring process.
- Check the data governance model should regularly against its performance.
- Enable data reuse for benchmarking current progress with past experiences. Data can also be used for product innovation by allowing controlled access to anonymised or aggregated datasets for:
    - R&D activities on new materials and technologies
    - The development of new CBMs (e.g. secondary markets, remanufacturing).
    - External research or funded projects, where appropriate.

4. Discussion and Conclusion

The deliverable shows that the use of the life-cycle-assessment as an integrated part of the technology development influenced the technology development, the product design and the business model development. It was possible to derive clear eco-design measures based on the LCA results, such as enabling the “re-use” of ICs with a high env footprint in a single use medical device through separating the “readout engine” containing the ICs from a disposable sensor patch. For printed electronics, the substitution of silver ink with copper or carbon-based inks can reduce the environmental footprint. However, moving away from silver ink to different formulations is not always easy due to the advantageous properties of silver. The use of bio-based substrates has limited benefits, and the biodegradation of electronics is still challenging due to non-biodegradable components and materials needed plus the current practice of incineration of medical waste due to its contamination. Important in that respect is to design for a realistic end-of-life scenario.

The LCA results also had an influence on the circular business model development, e.g. thinking about design for end-of-life and creating collection schemes also for refurbishment and parts harvesting or creating performance or access-based business models, especially for medical products where the value lies mainly in the data generated by the product. One important aspect regarding “data-driven” business models is to reduce the environmental footprint of the software but also understand how software and data can enable circular solutions (e.g. the DPP). The analysis also showed that the solutions can have positive social and environmental effects. For example, for health applications the devices from SUSTRONICS are representing an investment in materials and production to make an existing product smart by electronics (smart hygiene, smart wound dressing). The environmental and social benefits are originating from higher quality of care for the patient and reduction of hospitalisation and complications but also reducing workload on hospitals and health care staff. These environmental benefits are often also financial benefits that justify investments in R&D and introduction of intelligence to products.

Challenges to implement more sustainable solutions came from the lack of LCI data or only being able to collect data from processes in the lab that may differ from process being scaled and optimized. Although early LCA implementation allows for an easier (i.e. less costly) implementation of changes, there are also significant challenges associated. Beyond the obvious challenge of lacking data, functionality requirements can be more important by the product designers and trump environmental goals. In this context, including environmental considerations at the conception phase can be helpful to set realistic goals or more efficient strategies. For example, deciding whether a pilot is set to be an improvement over existing technologies from the get-go or whether the eco-design strategies will be centred around improving the early prototypes.

Many of the environmental issues identified during the LCAs of the pilots point outwards of the product design process. Here the limitations of LCA and eco-design in promoting systemic changes can be seen. Most of the challenges described above cannot be addressed exclusively by Original Equipment Manufacturers (OEMs), instead they require more extensive coordination and collaboration with other actors (e.g. suppliers, recyclers) or even changes in legislation and infrastructures that could allow for implementation of circularity strategies and more sustainable and ambitious CBMs.

Another limitation found is related to recycling. While printed electronics are not new, they still represent a tiny fraction of the e-waste which is still dominated by traditional rigid PCBAs. As the recyclability tests performed in the project show (Baaijens, 2025), current sorting equipment is not suitable to properly sort these types of e-waste. Potential solutions would require further coordination with recyclers for better sorting or exploring alternative recycling processes (e.g. printed assemblies on bio-plastics substrates could be separated through chemical recycling), which may require setting up new structures within OEMs such as take-back systems.

The compatibility of materials with production or recycling processes, and design trade-offs between sustainability, performance and costs were also complicating certain technology pathways, e.g. realizing modularity with reliable interconnection technologies user-friendly handling. To tackle those trade-offs, it is important to define obligatory specifications for key indicators (must meet) but also to allow for “wiggle room” with optional requirements or define ranges. Furthermore, in technology development no choice can be considered as stand alone. Another material in the set asks for compatibility between materials and compliance to the process window. If the process can be adjusted to the alternative material, other elements in the life cycle could be also optimised, for instance the eco-design supporting the recyclability of products. To ensure that the developed products and services are functional, it is critical to validate the developed solutions and adapt the solution for the use context. This needs to be iterated several times before scaling up the solution for pilots.

The overall Eco^{2}Design process framework is based on the activities within SUSTRONICS and includes technology development, environmental assessment, data management and software development, business model development, and the creation of a circular value network. However, within SUSTRONICS the processes were not always fully aligned as described in retrospective. Furthermore, activities related to piloting, validating, adapting, and scaling of the circular solutions go beyond the scope of SUSTRONICS, in general beyond the scope of an applied research project.

One important result is indeed to better align environmental assessment, technology and product development and business development. The examples showed that environmental improvements can be turned into added values for the end-user (e.g. more comfortable solution for patient), customers (e.g. more efficient processes in hospitals) and the circular value network partners (e.g. enhancing recyclability or providing product data). That means, that companies need to look beyond their own gates to develop together “win-win” solutions with end-users and partners and see the value of data for the whole network.

To advance the sustainability of electronics, it is crucial for companies and industry stakeholders to continue developing robust data standards and Digital Product Passports (DPPs) specifically for electronics. Institutionalising eco-design practices and Life Cycle Assessment (LCA) within both research and product development is essential for fostering innovation that prioritises environmental impact. Furthermore, investment in recycling technologies and supporting infrastructure tailored to printed electronics will help address current limitations in e-waste management. Establishing comprehensive take-back schemes for repair, refurbishment, parts harvesting, and recycling can enhance resource recovery and promote a circular economy. Cross-sector collaboration is vital for building circular ecosystems, particularly in tackling challenges such as data availability and improving recycling infrastructure. Companies should also create circular value networks, defining clear roles, responsibilities, and shared objectives, supported by governance frameworks and integrated data systems. As solutions scale, ongoing monitoring and adaptation of circular Key Performance Indicators (KPIs) will ensure continuous improvement and alignment with sustainability goals.

In the research domain, further studies are necessary to assess the recyclability of printed electronics, estimate realistic recycling rates, and generate Life Cycle Inventory (LCI) data for end-of-life treatment of new materials. Validating biodegradable solutions for relevant applications, such as in agriculture, alongside developing respective validation standards, can provide important insights into their environmental performance. Testing and validating the Eco^{2}Design framework during the scale-up of circular solutions and across various sectors and pilots will support its refinement and broader applicability. Furthermore, more data is required on bio-based and sustainable materials, as well as clear allocation methods for recycled and bio-based content. Integrating diverse data flows - including Digital Product Passports (DPP), Life Cycle Assessment (LCA), circularity metrics, and economic data - is crucial for holistic impact assessment, enabling a comprehensive evaluation of the environmental impact of circular value networks.

Policy makers play an important role in supporting these advancements by developing and promoting standards that ensure cleanliness, hygiene, and safety for medical devices, especially in cases where new material solutions such as bio-based or recycled materials are introduced. Addressing the limitations of recycling through the establishment of take-back schemes and the creation of biodegradation standards will further enable the transition towards a circular economy for the electronics sector.

Overall, the SUSTRONICS approach demonstrates how eco-design and CBM integration is feasible, impactful, and necessary for the future of European sustainable electronics. SUSTRONICS' technologies and approaches can support reaching the European climate targets and increase European sovereignty in electronics manufacturing relying on abundant and sustainable materials.

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Appendix A KPIs and validation approach for software

Table 5: Sustainable design recommendation to reduce the environmental footprint of software

Category	Recommendations	Example KPIs	Validation Approach
Energy Efficiency & Low Power	• Optimize algorithmic efficiency (reduce computation cycles) • Implement deep-sleep and low-power states • Use event-driven and threshold-triggered data transmission • Efficient communication protocols (BLE, optimized LoRa, etc.) • Minimize active time of device (AI-based triggers)	• Reduction in device/ system power consumption (%) • Absolute energy saved (kWh/year) • Battery lifetime extension (hours/days) • Power consumption per operation (mJ/op)	Compare measured energy use against baseline (legacy/ standard system) with power meters and device logs.
Resource-Efficient Firmware & Libraries	• Modular firmware supporting low energy operation • Efficient sensor data processing libraries • Fixed-point math to reduce computational load	• Code size (KB) • RAM usage (B) • Energy use per computation (mJ)	Profiling code with measurement tools; report reduction in resource use versus previous implementations.
Sustainable AI Design	• Model compression/ quantization • Optimized batch inference for efficiency • Off-device (cloud/ edge) computing for limited hardware	• Inference energy per query (kWh/query, CO2eq/query) • Memory use • Execution time per query (ms)	Measure using tools like CodeCarbon during inference and compare to common/baseline AI models.
Storage & Digital Infrastructure	• Erasure-coded storage for less redundancy • Modular, lightweight data handling • Minimal personal data retention (privacy by design)	• Storage over-provisioning (%) • CO2eq from storage use (kg/year) • Data retention periods (days/ months)	Quantify required storage and compare to replication-based previous solutions.

Table 6: Sustainable design recommendation to enable the reduction of the environmental impact through the software use

Category	Recommendations	Example KPIs	Validation Approach
Circularity & Resource Efficiency	• Decouple hardware-software lifecycle (enable remote, post-deployment firmware update) • Modular architecture to support the adaption e.g. to new sensors, hardware platforms, datasets or workflows and enabling updates and extensions • Support digital product passports for item lifecycle tracking • Digitize formerly paper-based workflows	• Increased product/ sensor/device lifetime (years/months) • Increase in reused/ recyclable components (%) • Reduction in paper/resource use (%) • # of remote updates performed	Measure device field longevity, track update events, monitor reduction in physical waste & materials use
Sustainable AI as an Enabler	• AI for predictive/personalized care (reducing unnecessary travel, interventions, resource use) • Synthetic data generation (less need for real-world subject recruitment) • Privacy-preserving inference to unlock new applications	• Reduction in patient/physician travel (#/year, km, CO2eq saved) • Waste/material prevented (kg/year) • AI-powered interventions avoided (e.g., unnecessary visits/test strips)	Compare usage scenarios (with and without the software) in pilot deployments; model/estimate savings using usage statistics.
Health & Societal Sustainability	• Enable home/remote monitoring for health (reduce travel, enable early intervention) • Digital dashboards for care coordination (replace physical reporting) • Support inclusive, accessible user interfaces	• CO2eq savings from reduced travel (kg/year, %) • # of patients/ caregivers with reduced visits • User and clinical adoption/ satisfaction metrics • Reduction in paper-based documentation (%)	Survey pilot outcomes: travel records, paper/ document use logs, user feedback/surveys.

Appendix B Structure of the data collection templates

Templates used in SUSTRONICS for software development (Soliman et al., 2025)

Table 7: Basic Information and technical description

Title of functionality:	[~ 100 characters]
Developed by (partner(s)):	[insert short names, lead partner first, followed by contributors]
Authors	[insert full names of persons contributing to writing]
Pilot(s):	[insert pilot numbers]
TRL start → end:	[insert]
Development status:	[Prototype / Tested / Deployed]
IP / Licensing status:	[Open source / Proprietary / Restricted]
Purpose and Scope (max 200 words)	[insert brief description of what the software does, its intended role, and why it matters, what were the requirements for the pilot]
System Architecture Diagram (mandatory, ~$^1/_2$ page figure + caption)	[insert schematic]

Table 8: Functional validation

Validation approach (max 200 words)	[methods, tests, environments used for validation]
Validation results (max 200 words)	[table, bullets, or short text; move detailed results to appendix, how pilot requirements were met]

Table 9: Sustainability Linkage

Sustainability Claim (max 150 words)	[insert text]
Sustainability KPIs	[insert text]
EU frameworks addressed (short list, e.g. CEAP / ESPR / DPP / EU AI Act)	[insert]

Table 10: Sustainability Validation

Validation approach (max 200 words)	[explain how KPIs were measured, baselines used, data sources]
Validation results (table/graph preferred, max 200 words)	[insert summary table/graph; detailed datasets go to appendix, what and how much resources are required]

Table 11: Pilot Integration, Lessons Learned & Reuse

Pilot integration & interoperability (max 200 words)	[describe how integrated into pilot, interaction with hardware/other SW, pilot requirements filled]
Lessons learned (max 200 words)	[sustainability limitations, trade-offs, unexpected outcomes]
Reuse & exploitation potential (max 200 words)	[possible applications beyond pilot, exploitation ideas, IP/licensing status]

Appendix C Pitfalls for scaling CBMs

Table 12: Common pitfall for scaling CBMs (Ellen MacArthur Foundation, 2025)

Why it makes CBMs fail	How to avoid / potential solutions
Thinking too small	
1. Lacking a plan for scale from the outset	
• Pilots run as one-off, local experiments-off, local experiments • Key ops/logistics for scale not considered • Heavy outsourcing means few internal learnings or ownership	• Define what “at scale, fully integrated” looks like from day one • Build a staged roadmap that tests key scale assumptions • Choose partners and pilot set-ups that can realistically scale (capacity, geography, role)
2. Missing the link to core business objectives	
• Framed as CSR/sustainability, not core business • Perceived as conflicting with brand, quality, or growth • Not linked to existing KPIs or bonuses	• Explicitly tie CBMs to growth, innovation, quality, and resilience • Embed circular targets into core design/innovation processes • Give ownership beyond sustainability; adapt language to each function and link to their KPIs
Strategic misalignment	
3. Mismatching the business model and organisation	
• Trend-driven model choice (e.g. resale, rental) without fit • Missing skills, processes, infrastructure for delivery • Capability gaps discovered mid-pilot, creating disillusionment	• Start with “easy entry” models that fit current strengths • Map required capabilities now and at scale; address gaps early • Use external partners or strategic investments to access missing capabilities
4. Neglecting customer experience	
• New steps (returns, repairs, subscriptions) feel complex • Experience separated from main channels, so low traffic • Marketing/service teams under-involved or unprepared	• Integrate CBMs into existing channels and journeys where possible • Focus on a high-potential segment and co-design the proposition • Engage and upskill marketing, sales, and service teams early
5. Overlooking product alignment	
• Products do not meet model demands (durability, repairability, desirability) • Poor margins and weak uptake in chosen product line • - “Wrong” product used to judge a promising model	• Test product-model-market fit explicitly before scaling • Start with products with strong demand or clear economics (incl. damaged returns) • Redesign products or choose a different circular model if fit is poor
Relying on a narrow business case	
6. Not leading with the financial narrative	
• Business case framed around sustainability or compliance • Finance and leadership see unclear or weak profit potential	• Lead with revenue, margin, and market-share opportunities • Involve finance early, model economics at scale and market size

Why it makes CBMs fail	How to avoid / potential solutions
• Longer payback vs. linear models not justified	• Strengthen economics via model “stacking” and cost-sharing collaboration
7. Using limited financial KPIs	
• Only short-term profit and loss metrics considered • Secondary value (customer lifetime value, brand strength, resilience) ignored • CBMs look weaker than linear offers in simple comparisons	• Broaden KPIs to include resilience, brand, and environmental value • Track customer metrics (perceived quality, brand trust) for CBM users • Quantify cost of inaction and risks of staying linear (materials, policy, climate)
8. Missing a long-term mindset	
• Deep changes (design, operations, behaviour) take longer than typical ROI windows • Pilots judged prematurely as “failed” • Leadership incentives biased to short-term performance	• Model long-term risks and returns, including supply and policy shocks • Build a phased roadmap combining near-term wins and long-term value • Share costs across functions; seek patient/green capital; use net present value across scenarios
Going it alone	
9. Not involving cross-functional teams and leaders	
• Pilots run in silos (often by sustainability/innovation) • Misaligned incentives (e.g. linear sales bonuses vs. circular revenue) • Lack of executive sponsors and cross-team ownership	• Map all functions needed at scale and tailor the value story to each • Co-create roadmap and shared KPIs, secure joint budgets • Set up a cross-functional steering group and adjust incentives to reward circular outcomes
10. Partnering ineffectively with external organisations	
• Partners chosen without clear plan for scale or mutual value • No access to needed customer/ops data; weak business case • Partner cannot scale geographically or operationally	• Decide early what to build vs. outsource and which partners are needed • Co-design partnerships with clear decision rights, scaling limits, and mutual benefits • Specify data collection, sharing, and ownership in contracts; evolve supplier relationships for circular needs