Assessing Product Circularity and Carbon Footprint: Electromagnetic Guard Locking System Case Study

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Abstract. Decarbonising industrial products without compromising material circularity is central to emerging "twin-transition" strategies, yet analysts still lack an operational method for evaluating both goals in one coherent study. This paper fills that gap by coupling the Product Circularity Indicator (PCI) with a streamlined product carbon-footprint (PCF) calculation in a transparent six-step workflow that mirrors the ISO 14040 life-cycle framework. We illustrate the approach on an industrial electromagnetic guard-locking system, generating a component-level hotspot matrix that displays each part's share of circularity impact (CII) alongside its PCF contribution. The baseline assessment exposes stark trade-offs: the polyamide housing dominates circularity, whereas the printed-circuit board accounts for three quarters of the PCF. Three progressively ambitious improvement scenarios are modelled. The most advanced—a product-as-a-service (PSS) concept that refurbishes the lock after one million duty cycles—cuts climate impact by 62% (from 7.1kg CO_2e to 2.7kg CO_2e) while more than doubling the PCI (0.23→0.59), with no adverse effects detected. Because the required input is limited to a bill-of-materials, basic recycling data and access to any mainstream LCA tool, a full assessment can be completed within days, making the procedure suitable for routine design reviews. The study thereby provides practitioners with a ready-to-use, quantitative decision aid for designing products that are both circular and climate-effective.

Keywords: Product circularity indicator · material circularity indicator · product carbon footprint.

1 Introduction

An increasing number of companies are seeking to understand the extent to which their operations and products contribute to GHG (greenhouse gas) emissions and their current impact on promoting a CE (circular economy). When not self-motivated, regulatory requirements across many regions worldwide compel them to do so [11, 24, 6, 9].

Indicators for assessment include the *Product Carbon Footprint (PCF)* and product circularity measures. Various methods calculate these indicators, with differing levels of user-friendliness. Companies generally favor more user-friendly methods when all other factors are equal.

Most companies rely on their existing product portfolios to generate revenue necessary for transitioning to less GHG-intensive, more circular operations. Thus, they need a user-friendly assessment method applicable to current products to evaluate circularity and PCF and identify improvement opportunities.

Companies can independently assess PCF and circularity, but evaluating them together is beneficial, as higher circularity often correlates with lower PCF, though not always. Joint assessment helps identify conflicts and guide strategy decisions.

Therefore, the objectives of our research are as follows.

1. Develop a procedure for assessing the environmental impact of a product that is:
   (a) **User-friendly** — easy to use by practitioners in the industry.
   (b) Applicable to **existing products** — helps users identify improvement potentials in their current product portfolio.
   (c) **Multi-dimensional** — assesses both a product's carbon footprint and its circularity, and lets users make informed decisions based on the goal conflicts that may arise.
2. Apply this method to a real-world case study (an existing product) in order to:
   (a) **Assess** the current PCF and degree of circularity of an existing product and
   (b) **Compare** strategies for improving PCF and circularity for this product.

Rather than inventing new methods, we build on the extensive body of research that already exists on measuring and mitigating the environmental impacts of products. Our contribution lies in integrating and streamlining established tools.

Section 2 explains how we selected an appropriate metric for product circularity and details its calculation. Section 3 outlines the unified procedure that combines PCF and circularity assessment. We demonstrate the procedure on a commercial product in Section 4, quantifying its circularity and carbon footprint and evaluating alternative improvement strategies. Section 5 discusses the findings and reflects on methodological limitations. Section 6 closes with a summary, conclusions, and avenues for future work.

2 Identifying a suitable method for assessing product circularity

To determine how far a product contributes to a CE, we first need a way to measure its circularity. Rather than devising a new metric, we surveyed the indicators already available to avoid reinventing the wheel.

A recent review by Luthin et al. [25] compares 133 CE indicators against six criteria:

- **Level** — scope from macro (regions) to micro (products or components);
- **Performance** — captures intrinsic circularity (e.g., recirculation rates);
- **Loops** — coverage of multiple R-Strategies [30] (see Section 3.6);
- **Units** — use of measurable physical units;
- **Dimension(s)** — multidimensional formulation;
- **Transversality** — applicability across industrial sectors.

For this study we require an indicator that operates at the micro level, measures intrinsic circularity, covers several R-Strategies, uses real units, is multidimensional, and is sector-agnostic.

Following those requirements—and the authors' recommendations—we select the *Product Circularity Indicator (PCI)* [5], an extension of the *Material Circularity Indicator* originally proposed by the Ellen MacArthur Foundation and Granta Design [8], as our circularity metric.

Subsection 3.3 details the PCI, its calculation, and its integration into our assessment workflow.

By contrast, PCF calculation relies on a mature life-cycle assessment (LCA) methodology already embedded in commercial software. We therefore discuss PCF only briefly (Section 3.4) and illustrate one possible implementation using such software.

3 Integrated procedure for assessing product circularity and carbon footprint

We begin with a high-level overview of the six-step procedure (Fig. 1) and then explain each step in detail.

The workflow intentionally mirrors the LCA framework in ISO 14040 [21]. Step 1 aligns with the goal and scope definition, Step 2 (*Collect & analyze data*) corresponds to the life-cycle inventory, and Step 4 (*Calculate carbon footprint*) matches an impact assessment limited to the global warming potential (GWP) category. Steps 5 and 6—*Identify improvement potential* and *Compare improvement scenarios*—parallel the interpretation phase. We add Step 3 to compute the PCI, thereby extending the ISO framework with explicit information on circularity.

The following subsections describe each step in turn.

3.1 Define goal & scope

The goal of this procedure is to quantify the PCI and the PCF and, where applicable, to compare scenarios designed to improve both metrics. The scope comprises three elements:

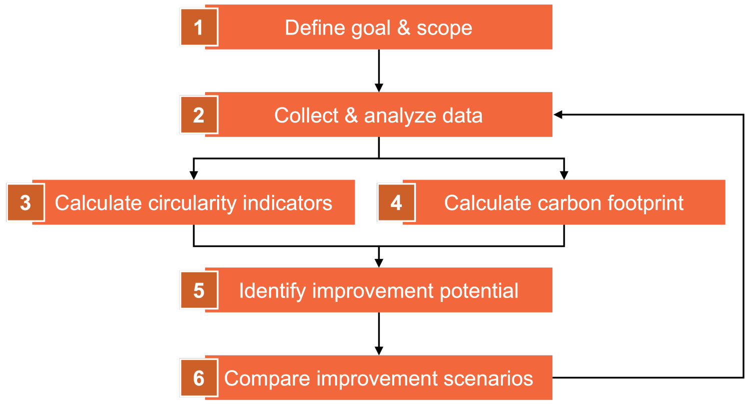

Fig. 1. Integrated six-step procedure for assessing product circularity and product carbon footprint (PCF). Step 6 (Compare improvement scenarios) feeds back to Step 2 (Collect & analyze data) because scenario analysis requires updated inputs.

- **Function** of the product system — the service the product delivers (for example, a light bulb illuminates a room).
- **Functional unit** — quantification of that service (for example, illuminating a 20m^2 room at an average illuminance of 1 000lx and a correlated color temperature of 4 000 K for one year).
- **System boundaries** — the life-cycle stages included in the assessment (for example, *cradle-to-grave*, meaning all stages from feedstock extraction to disposal).

Unless there is a clear justification, the default system boundary is cradle-to-grave. Analysts should narrow the scope (for example, to *cradle-to-gate*) only when essential data are unavailable or when a limited boundary can be convincingly defended.

3.2 Collect and analyze data

This step gathers all relevant information on material flows and manufacturing processes within the product system. Two inputs are required:

1. Bill of materials (BoM)
2. Input factors needed to calculate the circularity indicators

Bill of materials. The BoM should be as detailed as practicable and resolved to at least the lowest component level managed in-house. An example parts list appears in Table 1.

Next, aggregate the BoM entries by material while keeping the manufacturing processes for each material separate (Table 2).

Table 1. An example of a bill-of-materials (BoM) for a fictitious product.

Part	Material	Mass [kg]	Process
Rod	C45 steel	1.0	CNC-milling
Seal	Rubber	0.1	Injection-molding
Beam	C45 steel	1.2	CNC-milling
Cover	Polyamide	0.2	Extrusion
Plug	Polyamide	0.05	Injection-molding

Table 2. An example of a BoM for a fictitious product, aggregated by material and manufacturing process.

Material	Process	$\sum$ Mass [kg]	Mass fraction
C45 steel	CNC-milling	2.2	0.863
Rubber	Injection-molding	0.1	0.039
Polyamide	Extrusion	0.2	0.078
Polyamide	Injection-molding	0.05	0.02

As a final step, prepare a flow chart that links every process and material in the BoM (cf. Figure 2). The chart clarifies connections and dependencies within the product system.

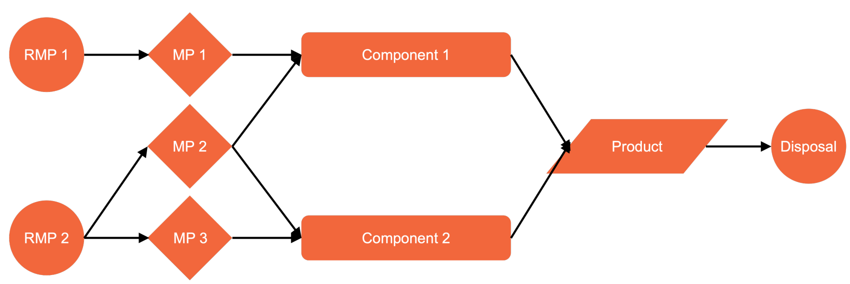

Fig. 2. Dummy flow chart for an exemplary product system. RMP = Raw material production, MP = manufacturing process.

Where complete information is unavailable, for example, when a component is purchased without disclosure of its composition or when a part is highly complex, analysts must rely on justified and documented assumptions or simplifications.

Input factors for calculating the circularity indicators. This part of the data-collection step is often the most labor-intensive. A firm database covering all in-house materials speeds the task, but additional sources are usually needed. Suitable life-cycle inventory (LCI) data can be drawn from commercial databases such as ecoinvent [41] and Sphera [34], from datasets bundled with tools like the Ansys Granta EduPack Eco Audit Tool [2], and from free resources such as, e.g., ProBas [39], Ökobaudat [13], or Agribalyse [7]. Any remaining gaps must be filled with clearly justified and documented assumptions.

Parameters on the material and component level:

- Recycling share in feedstock production, F_r
- Efficiency of feedstock production, E_{fp}
- Efficiency of component production, E_{cp}
- Share of feedstock-production losses recycled, C_{fp}
- Share of component-production losses recycled, C_{cp}
- Efficiency of material separation, E_{ms}
- Efficiency of recycling into new feedstock, E_{rfp}

Parameters on the product level:

- Total product mass, M
- Share of reused components in the product, F_u
- Reusable share of the end-of-use product, C_u
- Recyclable share of the end-of-use product, C_r
- Expected product lifetime (industry standard), L_d
- Actual product lifetime, L
- Expected product use intensity, I_d
- Actual product use intensity, I

Record all parameters in a spreadsheet, resolved to individual components where possible. The next subsection explains how these inputs feed into the circularity calculations.

3.3 Calculate circularity indicators

This study employs two metrics: the PCI and the Circularity Impact Indicator (CII). The PCI measures the overall circularity of the product, while the CII quantifies the contribution of each component to that circularity. The formulas are adapted from Bracquene et al. [5], with only minor changes in structure and terminology; the underlying logic is unchanged. Detailed calculation steps are given in Appendix A.

3.4 Calculate carbon footprint

This step corresponds to the impact-assessment phase of a LCA, but it is limited to a single impact category (GWP). Restricting the analysis to one category simplifies the work and draws on well-established models, whereas other categories, such as biodiversity, remain less mature [15, 32]. The drawback is that a focus on GWP captures only part of the environmental picture and can mask trade-offs among impact categories when evaluating mitigation options. Still, several impacts—though not all—correlate to some degree with GWP, depending on the product system [20, 18, 36]. For a practice-oriented method, the PCF is therefore a useful first approximation of environmental performance.

The calculation relies on the goal and scope from Step 1 and the data compiled in Step 2. A suitable software tool then generates the PCF. Tool selection depends on three criteria:

1. **Cost**: purchase price and recurring fees
2. **Functionality**: availability of features required for the analysis
3. **Ease of use**: effort needed to apply the software to the task

Costs range from free to several thousand U.S. dollars per year, depending on the tool and the type of license (for example, student, academic, or commercial).

A key functional requirement is access to LCI data for the background system (for example, electricity generation, feedstock production, and waste management). Primary data generally cover the foreground system (for example, onsite manufacturing), but the background must be modeled with secondary data from LCI databases. A tool that bundles such a database or is directly compatible with one offers a clear advantage. Other important features include built-in life-cycle impact-assessment (LCIA) methods (for example, GWP over a 100-year horizon, GWP_{100}, as defined by the Intergovernmental Panel on Climate Change [14]) and support for uncertainty analysis (for example, Monte Carlo simulation).

Ease of use depends on factors such as the presence of a graphical user interface and built-in visualization of results. Tools that rely on an integrated development environment without a graphical front-end require additional expertise and are less accessible to many users.

In short, practitioners can choose from a range of existing tools, balancing cost, functionality, and ease of use. The PCF result is expressed in kilograms of carbon-dioxide equivalents per functional unit, kg CO_2e/FU, where the functional unit is defined in Step 1.

3.5 Identify improvement potentials

This step pinpoints where modifications to the product will most effectively enhance both the PCF and the circularity metrics. Components that account for the largest share of the PCF and exhibit the highest CII provide the greatest leverage for improvement.

To locate these leverage points, list the results from the circularity analysis (Subsection 3.3) and the carbon-footprint calculation (Subsection 3.4) for every component, as illustrated in Table 3.

Improvement candidates are the components with the largest entries in the PCF-share and CII columns. The same table also reveals possible goal conflicts, such as a component with a high PCF share but a low CII (or vice versa). Using these insights, analysts can draft scenarios—material substitutions, design changes, or use-phase extensions—to reduce the product's carbon footprint, increase its circularity, or achieve both simultaneously.

Table 3. Exemplary table to identify improvement potential of a product by listing each component of the product and its share of the PCF (Product Carbon Footprint) and CII (Circularity Impact Indicator). Larger values equate higher potential for a component.

Component	Mass fraction	PCF share	CII
Component 1	$\frac{M_1}{M}$	$\frac{PCF_1}{PCF}$	CII_1
Component 2	$\frac{M_2}{M}$	$\frac{PCF_2}{PCF}$	CII_2
...	...	...	...
Component i	$\frac{M_i}{M}$	$\frac{PCF_i}{PCF}$	CII_i

3.6 Compare improvement scenarios

To develop and compare improvement scenarios, this study follows the Circularity Strategies within the Product Chain proposed by Potting et al.,[30]. The framework lists ten R-Strategies, from *R0–Refuse* to *R9–Recover*. In practice, greater circularity is achieved by giving preference to strategies with lower indices (R0 ahead of R1, and so on).

Work through the strategies in order, first assessing their relevance for the product system as a whole and then for each component. Begin with the component that accounts for the largest share of the product carbon footprint or the highest CII, then proceed in descending order. Whether to focus on footprint or circularity depends on the specific case and company priorities; no universal rule applies.

For any strategy–component pair, use the descriptions in Potting et al. [30] to identify concrete actions. For instance, *R2–Reduce* aims to increase efficiency in manufacture or use by consuming fewer materials and resources. Possible measures include adopting lightweight design to cut material use or modifying a process step to reduce scrap rates.

4 Applying the procedure to a case study

This section illustrates how the procedure outlined in Section 3 is applied to an industrial electromagnetic guard-locking system.

4.1 Case study: electromagnetic guard-locking system

The product under study is the electromagnetic guard-locking switch AZM 161 manufactured by K.A. Schmersal GmbH & Co. KG, Wuppertal, Germany (Figure 3). The switch functions as a safety interlock: when it is open, the associated machine cannot operate.

To protect intellectual property (IP), minor uncertainty was intentionally introduced during data collection (for example, by slightly adjusting material types or masses). These adjustments do not affect the validity of the procedure or the insights gained from the case study.

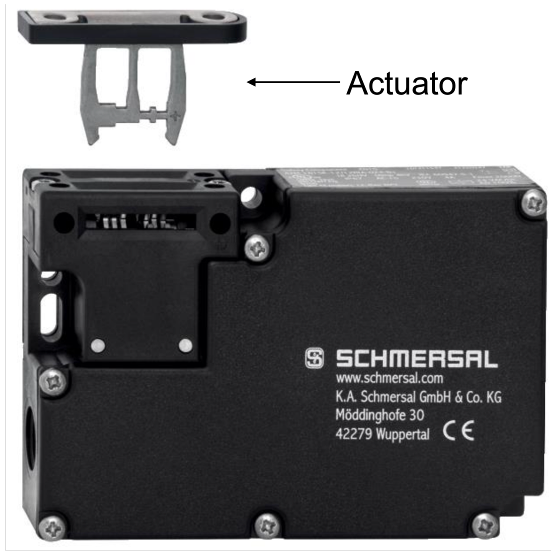

Fig. 3. Electromagnetic guard-locking switch AZM 161 (K.A. Schmersal GmbH & Co. KG).

4.2 Define goal and scope

The goal and scope are defined as follows:

- **Function**: Serve as a machine-safety switch.
- **Functional unit**: Secure one machine access gate for one year.
- **System boundary**: Cradle-to-grave, excluding the use phase.

The product system comprises the switch and its cardboard packaging, but not the actuator (cf. Figure 3) or any connecting cables. The use phase is excluded because no reliable data are available for that stage of the life cycle.

4.3 Collect and analyze data

Bill of Materials (BoM). Table 4 lists the BoM. Several physical parts have been aggregated into functional elements that represent them.

The case consists mainly of injection-molded polyamide (PA) components and stainless-steel screws made by cold forming. The locking mechanism contains PA, stainless steel, and brass parts, as well as die-cast aluminum discs. The magnet that actuates the lock is modeled by its principal subcomponents: frame (stainless steel), coil and wires (copper), and plunger (iron). The frame is assumed to be produced by a punching-and-bending process, based on an exemplary Kendrion solenoid [23]. The printed-circuit board (PCB) is treated as a black box and not further disaggregated.

Table 4. Bill of Materials for the case-study product system.

Part	Material	Mass [kg]	Process
Case	Polyamide	0.16	Injection molding
Case	Stainless steel	0.05	Cold forming
Locking mechanism	Polyamide	0.012	Injection molding
Locking mechanism	Stainless steel	0.006	Cold forming
Locking mechanism	Brass	0.010	Subtractive machining
Locking mechanism	Aluminum	0.025	Die casting
Magnet	Copper	0.025	Wire drawing
Magnet	Stainless steel	0.030	Punching and bending
Magnet	Iron	0.013	Subtractive machining
Printed circuit board	Mixed	0.020	Surface mounting
Packaging	Cardboard	0.050	Pressing and drying

Material and process masses are then summed, following the approach in Subsection 3.2 (details omitted for brevity). Figure 4 shows the corresponding material flow chart.

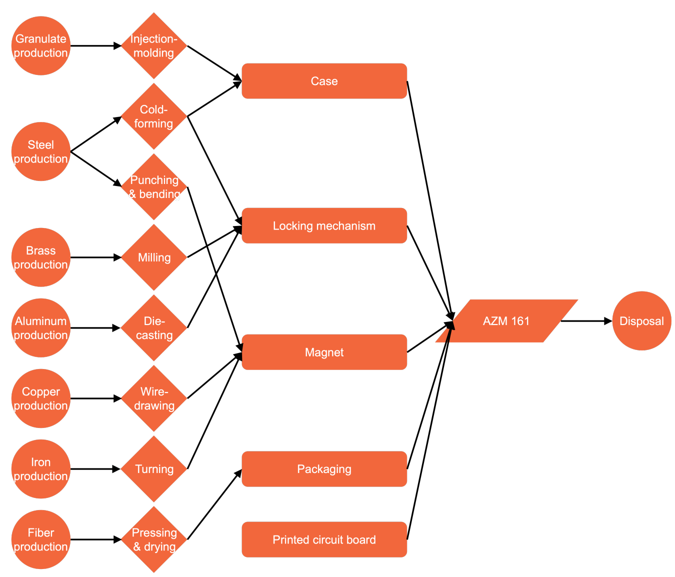

Fig. 4. Material flow chart for the case-study product system.

Input factors for calculating circularity indicators. Table 5 lists the input factors at the material and component levels. The assumptions underlying the table values are documented in Appendix B.1.

Table 5. Input factors for calculating circularity indicators at the material and component level for the case study product, including the value for each factor in percent (Val. [%]) and corresponding reference (Ref.) for each value. Values are rounded to one decimal if available at higher resolution.

Material (process)	F_r		E_{fp}		E_{cp}		C_{fp}		C_{cp}		E_{ms}		E_{rfp}	
	Val. [%]	Ref.	Val. [%]	Ref.	Val. [%]	Ref.	Val. [%]	Ref.	Val. [%]	Ref.	Val. [%]	Ref.	Val. [%]	Ref.
Polyamide (inj. molding)	0	x	100	x	95	x	0	x	100	x	30	x	30	x
Stain. steel (cold form.)	38	x	74.0	x	87	x	43.4	x	99	x	70.8	x	70.8	x
Stain. steel (punch/bend)	38	x	74.0	x	70	x	43.4	x	99	x	70.8	x	70.8	x
Aluminum (die-casting)	52.6	x	70.5	x	78	x	95	x	96.8	x	83.7	x	83.7	x
Copper	35.5	x	95.5	x	78	x	0	x	100	x	83.7	x	83.7	x
Brass (subtractive)	35.5	x	95.5	x	78	x	44	x	100	x	83.7	x	83.7	x
Iron (subtractive)	30	x	99	x	50	x	55	x	100	x	72.1	x	72.1	x
Cardboard	81.2	x	87.5	x	90	x	0	x	80	x	84.5	x	84.5	x
PCB	0	x	100	x	66.7	x	0	x	0	x	0	x	0	x

The remaining product-level factors are M, F_u, C_u, C_r, L_d, L, I_d, and I. The product mass is $M = 0.401\,\text{kg}$ (from Table 4). No components are reused ($F_u = 0$). Following [38], 60 % of discarded electrical products are collected ($C_u = 60\,\%$), and 86 % of those are actually recycled, giving a recycling rate of $C_r = 56\,\%$. Instead of L_d, L, I_d, and I, we directly adopt $FUDC$ and $FUDC_d$ as 1,000,000 cycles, based on manufacturer information [33, 4, 29]. The resulting use factor is therefore $X = 1$ (Equation 8).

4.4 Calculate circularity indicators

Using the input factors from the previous subsection, we calculate the PCI, CCI and CII (Table 6).

Table 6 shows that the injection-molded PA components have the lowest circularity (CCI = 0.024) yet dominate the circularity impact (CII = 64.6%). In contrast, the die-cast aluminum parts exhibit the highest circularity (CCI = 0.511) but contribute only 3.1% to the overall impact.

The product-level PCI and virgin feedstock mass V follow from Equations 1 and 2:

$$PCI = \frac{\sum_i M_i \cdot CCI_i}{M} = 0.229 \quad (1)$$

Table 6. Circularity indicators for the case study product system, CCI (Component Circularity Indicator) and CII (Circularity Impact Indicator). The CCI can take values ranging from 0 to 1, the CII from 0 to 100%. The mass and CCI values are rounded to three decimals, the CII values to one decimal.

Material	Mass [kg]	Process	CCI	CII [%]
Polyamide	0.172	Injection-molding	0.024	64.6
Stainless steel	0.011	Cold-forming	0.427	3.7
Stainless steel	0.030	Punching & bending	0.411	3.8
Brass	0.010	Subtractive	0.400	4.0
Aluminum	0.025	Die-casting	0.511	3.1
Copper	0.025	Wire-drawing	0.405	3.9
Iron	0.025	Subtractive	0.383	4.1
Cardboard	0.050	Pressing & drying	0.487	3.2
PCB	0.020	-	0.167	9.5

$$V = \sum_i V_i = 0.346 \tag{2}$$

Section 5.1 discusses these results.

4.5 Calculate carbon footprint

The PCF is determined with the AnSys EduPack Eco Audit Tool [2], selected for its cost effectiveness, functionality, and ease of use (Subsection 3.4). The software is free for students and was applied during a master's thesis. It offers all functions required for PCF calculation, a user-friendly graphical interface, and an LCI database that covers a wide range of materials and processes. Its main limitation is that it is not free for commercial users.

The tool requires specifications for materials, recycling shares, component masses, primary manufacturing processes, and end-of-life treatment. Appendix B.2 details how the case-study data were matched to the database and lists the associated assumptions. The resulting PCF is shown in Figure 5.

Figure 5 indicates that the injection-molded PA components contribute the most to the product mass and form the second-largest share of the PCF. The PCB, although it accounts for less than 6% of the mass (0.02 kg of 0.36 kg), dominates the PCF.

4.6 Identify improvement potentials

We combine each component's CII (Table 6) with its PCF share (Figure 5) and present the result in Table 7.

Table 7 shows a strong concentration of impacts: the PA casing dominates circularity (CII = 64.6 %), whereas the PCB dominates climate impact (75.4 % of the PCF). Guided by these findings, we outline three improvement scenarios.

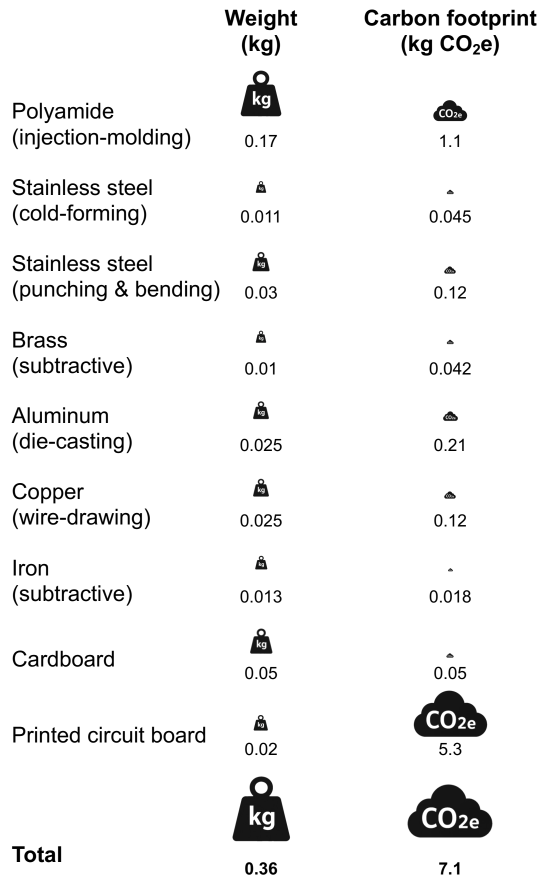

Fig. 5. Mass composition and PCF (product carbon footprint) for the case study product system, calculated using the AnSys EduPack Eco Audit Tool [2].

Table 7. Identifying improvement potentials for the case study product system, based on the CII (Circularity Impact Indicator) and PCF (Product Carbon Footprint) share of each component.

Component	Process	CII [%]	PCF share [%]
Polyamide	Injection-molding	64.6	16
Stainless steel	Cold-forming	3.7	0.6
Stainless steel	Punching & bending	3.8	1.7
Brass	Subtractive	4.0	0.6
Aluminum	Die-casting	3.1	3.0
Copper	Wire-drawing	3.9	1.7
Iron	Subtractive	4.1	0.3
Cardboard	Pressing & drying	3.2	0.7
PCB	-	9.5	75.4

R-Strategies *R0–Refuse* and *R1–Rethink* are impactful but better suited to new designs, so our first scenario applies *R2–Reduce*. Each scenario can draw on several R-Strategies.

1. Scenario S1: *R2–Reduce* and *R8–Recycle*
2. Scenario S2: *R3–Reuse*
3. Scenario S3: *R4–Repair*, *R5–Refurbish*, and *R6–Remanufacture*

Scenario S1. We increase recycled content in PA granulate from 0 to 20 %, redesign the casing to cut PA mass by 15 %, and eliminate the stainless-steel screws. The recycled share in aluminum feedstock rises from 52.6 % to 70 %. The PCB remains unchanged because the manufacturer has no design leverage.

Scenario S2. Customers discard the switch for three reasons: product defect, superior replacement, or machine retirement. Only the latter two allow reuse. We assume that 50 % of all units are returned, functionality-tested, and found to have 500 000 duty cycles remaining after the initial 1 M cycles.

Scenario S3. The firm offers a use-oriented product-service-system (PSS): it retains ownership, performs maintenance, and takes back the product. The locking mechanism, which limits life, is replaced after 1 M cycles. Magnets last up to 50 M cycles [1], and PCBs up to 20 years [37]; both are reused until 4 M cycles. The casing endures 2 M cycles; other parts, 1 M. Depending on the definition, this scenario involves repair, refurbishment, and/or remanufacture.

Table 8 summarizes how the input factors for calculating the PCF and PCI change from the Baseline Scenario to the Scenarios S1, S2 and S3.

Table 8. Changes in the input factors for the three improvement scenarios (S1–S3) for the case study product system relative to the Baseline Scenario.

Scenario S1	S2	S3
$F_{r,PA}$ $0 \rightarrow 0.2$	C_u $0.6 \rightarrow 0.25$	$C_{u,PA}$ $0.6 \rightarrow 0.47$
$F_{r,Al}$ $0.526 \rightarrow 0.7$	F_u $0 \rightarrow 0.25$	$F_{u,PA}$ $0 \rightarrow 0.47$
$M_{PA,casing}$ 160 g $\rightarrow$ 136 g	-	$C_{u,st.steel}$ $0.6 \rightarrow 0.34$
$M_{PA,total}$ 172 g $\rightarrow$ 148 g	-	$F_{u,st.steel}$ $0 \rightarrow 0.34$
$M_{st.steel,casing}$ 50 g $\rightarrow$ 0 g	-	-

4.7 Compare improvement scenarios

The scenarios' effects on the product's key indicators are summarized in Table 9.

Scenario 3 delivers the largest reduction in PCF and the highest increase in PCI, followed by Scenarios 2 and 1. The ranking is consistent—each scenario improves both metrics compared with its predecessor—so no trade-off arises (Figure 6).

Scenario 3 is therefore the preferred option for simultaneously lowering the PCF and raising the PCI.

Table 9. Resulting change in the key indicators, PCF (Product Carbon Footprint) and PCI (Product Circularity Indicator), from the three improvement scenarios for the case study product system (abs = absolute, rel = relative).

Scenario	PCF [kgCO$_2$e]	$\Delta PCF_{\mathrm{abs}}$ [kgCO$_2$e]	$\Delta PCF_{\mathrm{rel}}$ [%]	PCI [-]	$\Delta PCI_{\mathrm{abs}}$ [-]	$\Delta PCI_{\mathrm{rel}}$ [%]
Baseline	7.1	-	-	0.227	-	-
S1	6.7	-0.36	-5	0.298	+0.71	+31
S2	6.2	-0.92	-13	0.433	+0.206	+91
S3	2.7	-4.4	-62	0.589	+0.362	+160

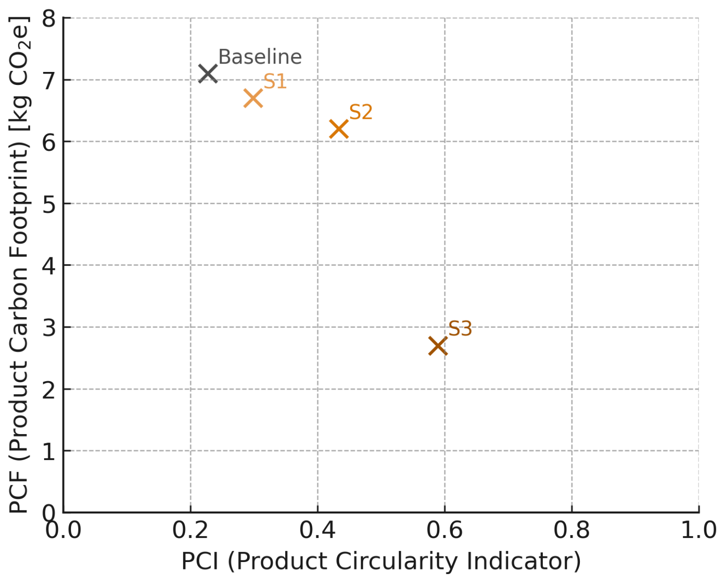

Fig. 6. Comparing results for Scenarios 1-3 of the case study product system, referenced to the Baseline Scenario.

5 Discussion

This section reflects on the results, the proposed method, and the limitations that apply to both.

5.1 Discussion and interpretation of results

Because no accepted benchmarks exist, it is hard to judge whether the baseline PCF of 7.1 kg CO_2e and PCI of 0.227 represent good performance. An ideal product would have a PCF of 0 and a PCI of 1, so the baseline merely indicates improvement potential.

Scenarios S1–S3 provide additional insight. The most ambitious option, S3, lowers the PCF to 2.7 kg CO_2e (–62 %) and lifts the PCI to 0.589 (+160 %). These figures show what is technically possible. We do not label specific PCF or PCI ranges as good or poor, as such judgments are subjective; future research could propose objective thresholds.

A component-level analysis of the baseline PCF reveals that the PCB accounts for only a small mass share yet 75.4 % of total emissions. The PCB is therefore a hotspot; a smaller or lower-spec board could cut emissions. By contrast, the PCI is dominated by the polyamide (PA) housing (64.6 %). Circularity could be raised by cutting PA mass, adding recycled PA, securing end-of-life recycling, or switching to a more recyclable material.

Performance improves monotonically across scenarios (S3 > S2 > S1 > baseline) with no trade-off between PCF and PCI. S3 lies well outside the cluster of the other three, confirming that a use-oriented PSS with remanufacturing or refurbishment is most effective, followed by reuse (S2) and incremental redesign with design-for-recycling and lightweighting (S1). This hierarchy aligns with earlier studies on the environmental potential of use-oriented PSS [**?**]. The ranking is sensitive to parameters such as lifetime extension and recycling rate, but the analysis underscores the promise of use-oriented PSS and merits further work on practical implementation.

Result limitations

- Case-study realism — Scenarios S1–S3 are hypothetical; only the baseline reflects an actual product, limiting external validity.
- Confidentiality masking — Selected data were aggregated or altered for IP reasons, introducing small deviations.
- Dataset sensitivity — Results hinge on the built-in LCA database; switching to ecoinvent or Sphera would likely change both PCF and PCI. Proper metadata and technological/spatial/temporal alignment are crucial.
- Benchmark gap — No earlier study reports both PCF and PCI for this product type, preventing direct comparison. Future work should contrast the method with GWP-only LCAs and test alternative databases to gauge variability.

Scenario limitations:

S1: cannot be modeled to 100 pc fidelity. "Da das Fertigungsverfahren nur einen vernachlässigbaren Teil des Carbon Footprints ausmacht, wird der Recyclinganteil im Polyamid dadurch modelliert, dass 80 pc des Materials weiterhin als Neumaterial eingetragen werden. Der Recyclinganteil wird als zusätzliche Komponente hinzugeführt, bei der als Recyclinganteil Wiederverwendetes Bauteil angegeben wird. (siehe Abbildung 14)." (muss geklärt werden - verstehe ich nicht). aluminum recycling rate cannot be changed and remains the same.

S2: Same as S1, the recycling rate is modeled by reducing mass of component and adding a second component with 0 pc virgin / 100 pc recycled content (feedstock).

S3: Similar approach to S2.

5.2 Discussing the method

The study had two objectives: i) to devise a practitioner-oriented procedure that combines PCF and PCI assessments; and ii) to apply it to a commercial product to compare improvement strategies. Both objectives were met.

The six-step workflow builds on established LCA principles and aligns with current standards and practitioner expertise. Every step is documented, PCI can be calculated in a spreadsheet or script, and PCF can be obtained with any mainstream LCA tool offering a graphical interface. The approach is therefore usable by stakeholders with varying skills and resources. Reporting PCF and PCI side by side reveals synergies and trade-offs that a single metric would hide, enabling hotspot detection and informed strategy selection.

However, some limitations regarding the method remain.

Methodological limitations

- Software access — The Ansys EduPack Eco Audit Tool is commercial; free licences are restricted to students, which limits industry uptake.
- Indicator scope — Only global warming potential is quantified; other impacts (e.g. abiotic resource depletion, water use, biodiversity loss) are excluded.
- Background data — Results depend on the default Ansys database. The tool cannot import alternative datasets (e.g. ecoinvent, Sphera), hindering regional or technological sensitivity analysis.
- Uncertainty — Single-point parameters were used; stochastic approaches such as Monte Carlo simulation are not yet implemented.
- Data requirements — A detailed BoM is mandatory; the method is unsuitable for concept-stage products lacking such data.
- PCI validity — PCI assumes equal recyclability across materials. The analysis flags PA as the circularity hotspot, yet PCBs may be less recoverable despite their lower PCI share due to the challenges in recovering metals from complex products [31].

Addressing these issues—especially broader indicator coverage, uncertainty analysis, and a refined circularity metric—will enhance the method's robustness and applicability.

6 Summary, Conclusion and Outlook

This paper proposed and demonstrated an integrated, six-step procedure that allows practitioners to jointly assess a product's circularity and climate performance by coupling the Product Circularity Indicator (PCI) with a streamlined product carbon-footprint (PCF) calculation.

Key contributions

1. A practical workflow that mirrors the ISO 14040 life-cycle-assessment framework while adding an explicit circularity step. All data requirements, equations and software choices are transparent so that engineers can replicate the analysis with nothing more than a detailed bill-of-materials and access to a mainstream LCA tool.
2. A component-level hotspot screen that combines the Circularity Impact Indicator (CII) with the per-component PCF share, enabling users to pinpoint improvement levers and to visualise potential trade-offs early in the design process.
3. The first (to the authors' knowledge) published application of the method to an industrial electromagnetic guard-locking system. The baseline study revealed a highly uneven impact distribution: the polyamide (PA) housing dominated circularity (CII = 65%), whereas the printed-circuit board (PCB) generated three quarters of the PCF. Three improvement scenarios were modelled. The most ambitious one—a use-oriented product–service system that refurbishes the lock after one million duty cycles—reduced the PCF from 7.1kg CO_2e to 2.7kg CO_2e (–62%) and increased the PCI from 0.23 to 0.59 (+160%), with no adverse trade-off observed.

Conclusions

1. Reporting PCI and PCF side by side provides richer insight than either metric alone and can reveal synergies that remain hidden in single-indicator studies.
2. Even for mature electromechanical products, large circularity and climate gains are technically feasible when business models shift from ownership to performance-based service.
3. The approach is intentionally lightweight: once the BoM and basic recycling data are available, a complete assessment—including scenario modelling—can be completed within a few working days, making the method suitable for routine design reviews.

Outlook

1. **Broader impact coverage**—adding toxicity, water and biodiversity indicators will mitigate the current "carbon hyper-focus."

2. **Uncertainty analysis**—propagating parameter ranges through Monte-Carlo simulation would provide decision makers with robustness metrics rather than single-point estimates.
3. **Refined circularity metrics**—future work should incorporate material criticality and recovery efficiency (e.g. for PCBs) to avoid overstating the circular potential of components that remain difficult to recycle in practice.
4. **Industry roll-out**—applying the procedure to families of products across multiple sectors will build the empirical basis needed for benchmarking and will test transferability to other circular-business-model archetypes.

In summary, the proposed procedure closes a methodological gap by operationalising the simultaneous evaluation of circularity and carbon footprint at product scale. Its successful application to a real-world safety lock confirms its practicality and highlights the substantial sustainability benefits that design-for-circularity, smart material choices and service-oriented business models can unlock.

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A Appendix: Calculation of circularity indicators

The PCI is calculated like this:

$$PCI = \frac{\sum_i (M_i \cdot CCI_i)}{M} \tag{3}$$

Where M_i is the mass of an individual component i, CCI_i the *Component Circularity Index (CCI)* (not to confuse with the Circularity Impact Indicator (CII)) of this component, and M the total mass of the product. Just like the PCI is the degree of circularity of an entire product, the CCI is the degree of circularity of an individual component of that product.

The CII of a component i is calculated like this:

$$CII_i = \frac{100 \cdot PCI}{CCI_i \cdot \sum_i \frac{PCI}{CCI_i}} \tag{4}$$

The PCI and the CCI can take values ranging from [0...1], where 0 represents no circularity at all (full linearity), and 1 represents full circularity. The CII can take values ranging from [0...100]%, where 0% represents no influence on a product's circularity, and 100% represents total influence on a product's circularity.

Now we have defined PCI as a function of component mass, product mass, and CCI; as well as CII as a function of PCI and CCI. The next step is to define PCI and CCI as functions of the input factors described in Subsection 3.2. To do that, we work our way backwards from PCI and CCI to the input factors.

Figure 7 visualizes an exemplary product system, including all the material flows within the system, and the input factors listed in Subsection 3.2.

The visualization may help to get a better understanding of all the variables in the equations that follow, and how they relate to one another.

Now we will go step by step through the process of how to calculate the circularity indicators, moving backwards from the indicators to the input factors. Let's start with the PCI:

$$PCI = 1 - \frac{LFI}{X} \tag{5}$$

Where LFI is the *Linear Flow Index* and X is the product use factor. This equation illustrates that for very small values of X, the PCI may in fact become negative. In this case, the PCI is set to 0.

The CCI is calculated in the same way as the PCI, with the only difference that the CCI refers to component i that is part of the whole product which the PCI represents:

$$CCI_i = 1 - \frac{LFI_i}{X_i} \tag{6}$$

That means that all the following equations refer to both the product and component level, where the component level is denoted by the index i. The input

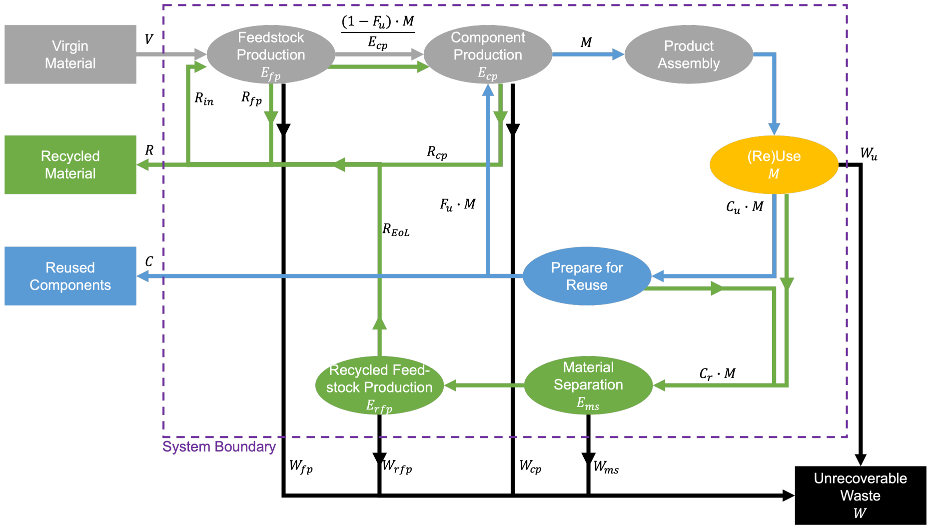

Fig. 7. Exemplary product system including all material flows, based on (ref Braquene).

factors have to be adjusted and chosen accordingly. In some cases, the factor at the product level propagates to the component level (e.g. actual product use intensity I). For simplicity's sake, only the calculations at the product level are shown in the following equations.

The LFI is calculated like so:

$$LFI = \frac{V + W + \frac{1}{2} \cdot |R| + \frac{1}{2} \cdot |C|}{V_{linear} + W_{linear}} \tag{7}$$

Where V is the virgin feedstock mass, W is unrecoverable waste mass, R is the recycled material mass, C is the reused component mass, V_{linear} is the linear share of the virgin feedstock mass, and W_{linear} is the linear share of the unrecoverable waste mass.

Before we continue breaking down these equations even further, we first have to explain how the product use factor X (cf. Equations 5 & 6) is calculated:

$$X = \frac{FUDC}{FUDC_d} = \frac{I \cdot L}{I_d \cdot L_d} \tag{8}$$

Where $FUDC$ is the actual number of functional usage duty cycles, $FUDC_d$ is the expected number of functional usage duty cycles, I is the actual product use intensity, L is the actual product lifetime, I_d is the expected product use intensity, and L_d is the expected product lifetime. Since I, L, I_d and L_d are collected in the previous step (cf. Subsection 3.2), we are at the end of this sub-journey, and turn our attention to another sub-journey, the terms introduced in Equation 7.

The virgin feedstock mass V is calculated like so:

$$V = \frac{(1 - F_u) \cdot M}{E_{cp} \cdot E_{fp}} \cdot (1 - F_r) \tag{9}$$

Where F_u is the share of reused components in the product, M is the total product mass, E_{cp} is the efficiency of component production, E_{fp} is the efficiency of feedstock production, and F_r is the recycling share in feedstock production. Again, since all these values are collected in the previous step (cf. Subsection 3.2), we have completed yet another sub-journey.

Continuing with the terms introduced in Equation 7, we next define the unrecoverable waste mass W:

$$W = W_{fp} + W_{cp} + W_u + W_{ms} + W_{rfp} \tag{10}$$

Where W_{fp} is the waste mass from feedstock production, W_{cp} is the waste mass from component production, W_u is the waste mass for incineration and disposal, W_{ms} is the waste mass from material separation, and W_{rfp} is the waste mass from recycled feedstock production.

Each of these waste mass terms W_x is calculated from input factors defined in Subsection 3.2. Let's list them all in a row here:

$$W_{fp} = \frac{(1 - F_u) \cdot M}{E_{fp} \cdot E_{cp}} \cdot (1 - E_{fp}) \cdot (1 - C_{fp}) \tag{11}$$

$$W_{cp} = \frac{(1 - F_u) \cdot M}{E_{cp}} \cdot (1 - E_{cp}) \cdot (1 - C_{cp}) \tag{12}$$

$$W_u = M \cdot (1 - C_u - C_r) \tag{13}$$

$$W_{ms} = M \cdot (1 - E_{ms}) \cdot C_r \tag{14}$$

$$W_{rfp} = M \cdot E_{ms} \cdot (1 - E_{rfp}) \tag{15}$$

Where F_u is the share of reused components in the product, M is the total product mass, E_{fp} is the efficiency of feedstock production, E_{cp} is the efficiency of component production, C_{fp} is the share of feedstock production losses being recycled, C_{cp} is the share of component production losses being recycled, C_u is the reusable share of an end-of-use product, C_r is the recyclable share of an end-of-use product, E_{ms} is the efficiency of material separation, and E_{rfp} is the efficiency of recycling.

Having defined all waste mass terms W_x, we can now turn our attention to the recycling mass terms R_x (cf. Equation 7). The absolute value for the flow of recycling material within the product system, $|R|$, is the difference between the amount of recycling material flowing into the product system R_{in} and the amount of recycling material leaving the product system R_{out}:

$$|R| = R_{in} - R_{out} \tag{16}$$

Where R_{in} is defined as:

$$R_{in} = \frac{(1 - F_u) \cdot M}{E_{fp} \cdot E_{cp}} \tag{17}$$

R_{in} is thus fully defined by the input factors from Subsection 3.2. R_{out} is defined as:

$$R_{out} = R_{fp} + R_{cp} + R_{EoL} \tag{18}$$

Where R_{fp} is the scrap mass flow from feedstock production, R_{cp} is the scrap mass flow from component production, and R_{EoL} is the mass flow of recovered material from the product End-of-Life. These three terms are defined like so:

$$R_{fp} = (1 - E_{fp}) \cdot E_{cp} \cdot \frac{(1 - F_u) \cdot M}{E_{fp} \cdot E_{cp}} \tag{19}$$

$$R_{cp} = (1 - E_{cp}) \cdot C_{cp} \cdot \frac{(1 - F_u) \cdot M}{E_{cp}} \tag{20}$$

$$R_{EoL} = E_{rfp} \cdot E_{ms} \cdot C_r \cdot M \tag{21}$$

Now all R_x terms are fully defined by the input factors from Subsection 3.2. We can therefore turn our attention to the reused component mass C (cf. Equation 7), which is defined as:

$$C = M \cdot (F_u - C_u) \tag{22}$$

Where all terms are input factors from Subsection 3.2. That leaves V_{linear} and W_{linear} as the only terms that are yet to be defined (cf. Equation 7). Since these are the mass flows for the cases where no components are reused and no material is recycled ($F_r = F_u = C_u = 0$, cf. Figure 7, these terms are defined as::

$$V_{linear} = W_{linear} = \frac{M}{E_{cp} \cdot E_{fp}} \tag{23}$$

That concludes the calculation of the product circularity indicators, as all values are defined by the input factors.

B Appendix: Case study assumptions

B.1 Assumptions for the values listed in Table 5

All materials & components Since no material-specific values for E$_{ms}$ and E$_{rfp}$ could be found, they were approximated using an overall recycling rate R$_R$:

$$E_{ms} = E_{rfp} = \sqrt{R_r} \tag{24}$$

Polyamide (PA) The values for E_{fp}, E_{cp}, C_{fp} and C_{cp} are extracted from Kawecki et al. [22], also cited in the original Bracquené et al. paper [5]. The source does not mention PA specifically, but instead covers seven types of polymers commonly used in Europe. The values for PA are adapted from these other polymer types. It is further assumed that for the baseline scenario, no recycled PA is used ($F_r = 0$). The recycling rate R_r is assumed to be 9%, based on Hirschberg & Rodrigue [19], resulting in an E_{ms} and E_{rfp} of 30%.

Stainless steel All values are adapted from the Bracquené et al. paper [5]. The recycling rate R_r is assumed to be 38% in the material, based on [5]. A report by the European Recycling Industries Confederation (EuRIC) shows that stainless steel products in Europe already achieve a recycling rate of 90% today and that the recycling rate of raw steel produced worldwide is 35.5% [10]. Due to a lack of literature data on In the absence of literature data on average material yields in punching processes, an average efficiency of 70% is assumed here. The recycling rate for the residual material produced during the punching process is also assumed to be 38%.

Aluminum For aluminium, the data used in the case study by Bracquené et al. for production efficiencies is used [5]. The Metal Recycling Factsheet specifies a recycling rate of 69% [10]. This corresponds to the 70% end-of-life recycling rate specified in the Recycling Report of the UN Environment Programme [16]. Furthermore, the UN Report states an average recycling rate of 50% in the material [16]. Due to the similar process, the same production efficiency is assumed for the die casting process as for plastic injection moulding.

Copper For copper, the efficiency values can be taken directly from the work of Bracquené et al [5]. The recycling data for copper can also be taken from the EuRIC report, which states that 44% of European copper demand is met by copper scrap and that a recycling rate of 70% is achieved [10].

Brass Due to a lack of literature data, the same efficiency values are used for brass as for copper. According to the United Recycling Report, the recycling data for copper and tin, the main components of brass, are almost identical and are therefore also treated with the data for copper [16]. For subtractive processing methods, such as in the case of brass components, a material utilisation of 44% is assumed [27].

Iron For iron, Gramlich and Krupp state that 70% of the steel produced is obtained by the primary method, i.e. from the reduction of iron ore. This corresponds to a recycling rate in steel production of 30% [17]. The recycling rate is stated as 52% for 2009 in the United Nations Environmental Programme's Metal Recycling Report [16]. As no precise data on pure iron production could be found, the raw material production efficiency of steel is taken from Bracquené et al. [5], and the proportion of recycled production losses is set at 55%, based on a material flow analysis of iron in Europe [28].

Cardboard For cardboard, Monte et al. estimate production losses in the manufacture of paper and cardboard at an average of 159 kg per tonne of paper produced, based on data from three manufacturers. Another manufacturer with a reported figure of 23 kg/tonne is not included due to a lack of recycling data [26]. The amount of recycled waste for the three manufacturers ranges between 115 and 138 kg/tonne, with an average of 130 kg/tonne. This results in a production efficiency of 86.2% and a waste recycling rate of 81.6%. The recycling rate in corrugated board production is estimated by the Corrugated Board Industry Association at 81.2% for 2022; this figure is also used for cardboard due to sufficient similarity [35]. The recycling rate for paper and cardboard is estimated at 71.4% for 2021 in the Monitoring Report of the European Paper Recycling Council [12].

Printed circuit board A material flow analysis of printed circuit board production conducted by Wang et al. indicates a material-related production efficiency of 66.7% [40]. The Wuppertal Institute has published a study on the recycling rates of technology metals, which are also used in printed circuit boards [42]. However, due to their very low mass fraction, these are not considered in this context, and it is assumed that the recycling rate is 0%.

B.2 Assumptions for calculating the product carbon footprint (Section 4.5)

Add assumptions here (Masterarbeit Abschnitt 5.4.2)

The Eco Audit user interface requires information on materials, recycled content, mass, primary processing and end-of-life treatment. For each component, a material, recycled content, mass, primary process and end-of-life treatment must be specified. The primary processes describe the manufacture of the basic materials of the respective components. Since only the manufacturing process of the component has been specified for the components so far, a suitable selection must be made here.

The plastic chosen is a glass fibre-reinforced PA6 with flame retardant, as used for switches and contact carriers [3]. The primary production process is polymer casting. For the stainless steel components, a common austenitic stainless steel is specified; the processing process is described as wire drawing for cold forming and roll forming for the stamped-bent part. The brass component is represented by a component made primarily by forging from CuZn28Sn1, a corrosion-resistant copper-zinc alloy, as there is no possibility of specifying a second, subtractive machining process for a material. AlSi6Cu4, a material commonly used for die casting, is selected to represent the aluminium components. For the copper component in the solenoid and wiring, drawn C12500 copper was used, and for the iron component, a forged component made of ferromagnetic iron. Cardboard is selected as the packaging material, and the circuit board is represented by a laptop circuit board of the same weight.

The next step is to provide information on transport routes and means of transport and to define the service life of the product. In this case, the transport route is specified as 500 km in order to approximate the average transport route within Europe. Since the service life is specified as a mechanical service life of one million switching cycles, the service life is specified as one year in the calculation. [33]