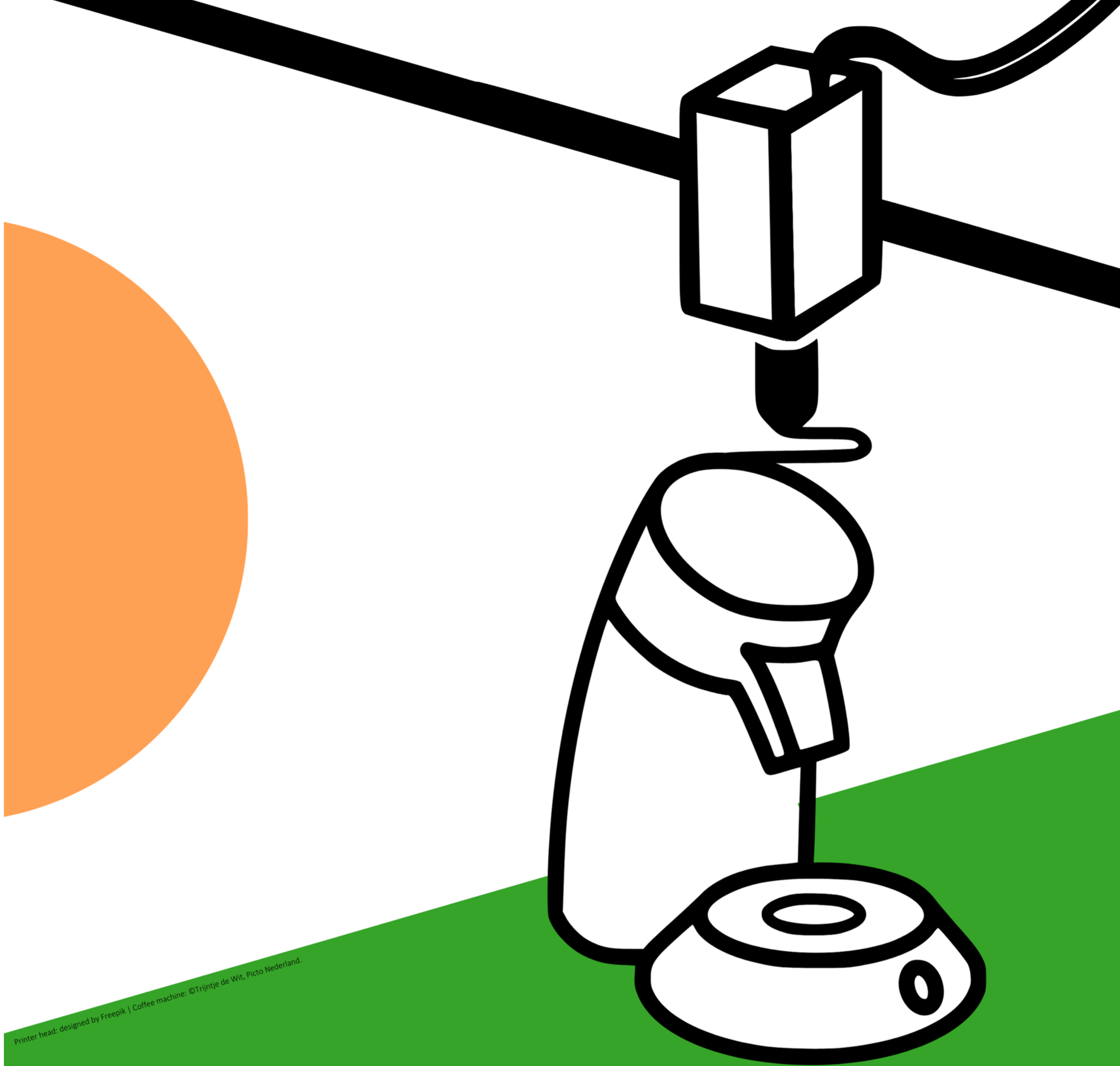

Printer head: designed by Freepik | Coffee machine: ©Trijntje de Wit, Picto Nederland.

To print or to purchase: a case study about the environmental impact of 3D printing for repair.

Master Thesis report

Lucas Nijhof | 3685179 | 5889200

First supervisor: Jeremy Faludi | Second supervisor: Nils Thonemann

MSc Industrial Ecology | Technical University of Delft | University of Leiden

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Abstract

The environmental impact of additive manufacturing (AM) in consumer-electronics repair remains largely unexplored. AM allows on-demand production of spare parts, making it possible to repair products without available replacement parts (RPs). However, its per-part impact is higher than conventional injection molding (IM). When no digital part exists, redesigning it—such as through the 3DPfR framework—often requires multiple testing and printing iterations, further increasing its environmental impact. Literature focusses on either emphasizing qualitative approaches like AM-enabled sustainable design strategies or quantitative life cycle assessment studies that overlook these trade-offs and the broader system dynamics. Few take a systematic, quantitative approach to evaluating AM in the context of product repair. This study addresses this gap through a life cycle assessment case study of the Philips Senseo HD6569/00 coffee machine.

The following input variables are defined: lifetime extension, part mass and five responses to product failure (RtPF). The five RtPFs are compared in this study are: product replacement (Replace), repair using a single injection molded RP (IMRP), IMRP including *n* overproduced IM RPs (IMRP-*n*), on-demand RP production using a pre-existing AM-ready digital model (AMRP), and using the 3DPfR framework to design an RP for AM and requiring n printing iterations to achieve an acceptable part (AMRP-*n*).

LCA is employed as the primary method due to its ability to systematically and quantitatively assess environmental impacts across an entire product lifecycle. The study uses ReCiPe 2016 (Hierarchist) to evaluate environmental impact midpoint categories, with the functional unit defined as "providing one year of coffee machine use for a consumer in the Netherlands". The study takes a cradle to grave approach, including a logistics scenario, but excludes the machine's use-phase impacts. The next phase of the study involves performing a sensitivity analysis and contribution analysis as well as depicting tipping points between different repairs compared to product replacement.

The study defines one alternative as environmentally 'favorable' over another if it has a lower impact score in all impact categories compared to its alternative. Results identify electricity consumption during printing, 3D printer production, and RP material impact differences as key drivers of AM's increased environmental impact over IM. As a result, AM-based repairs always lead to a higher environmental impact compared to IM-based repairs. This difference becomes more evident when additional AM print iterations are required, or the number of overproduced IM parts increases. When comparing repair to product replacement, IM-based repairs are far more likely to be environmentally favorable over product replacement compared to AM-based repairs. Therefore, the number of IM overproduced parts is not considered a sensitive variable, whereas the number of print iterations is. However, the exact tipping point is highly depending on the input variables.

IM-based repairs should be prioritized whenever available. If no IM RP is accessible, minimizing the number of AM print iterations is crucial, with single print-on-demand manufacturing being the most favorable option. When neither an IM RP nor an on-demand AM RP is available, a part can be redesigned using the 3DPfR framework. In this case, the environmental favorability of repair over replacement depends on the number of required print iterations, part mass, and expected lifetime extension, and careful assessment should be made. While the scenario evaluation tool developed in this study provides insights into these trade-offs, its findings are highly context dependent. If AM RPs designed via 3DPfR contribute to an open-source, on-demand manufacturing library, their broader sustainability benefits may justify their initial environmental impact.

The impact of overproducing IM RPs is less significant compared to the number of AM iterations. Specifically, for the same part mass and lifetime extension, producing 10 IM RPs or performing 2 to 6 AM print iterations can be environmentally favorable over product replacement, depending on the packaging type used for transporting the IM RPs.

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List of abbreviations

3DPfR	3D Printing for Repair framework
AMRP-*n*	additive manufactured replacement part designed using '3D Printing for Repair framework' – one of the RtPFs
AM	Additive Manufacturing/manufactured
AMRP	Additive Manufacturing Ready replacement Part – one of the RtPFs
BOM	Bill Of Materials
CA	Contribution Analysis
CE	Circular Economy
CM	Coffee Machine
EEE	Electrical and Electronic Equipment
EoL	End of Life
FU	Functional Unit
IC(s)	Impact Category(ies)
IM	Injection Mold/Molded
IMRP-*n*	Injection Molded Replacement Part – one of the RtPFs
LCA	Life Cycle Assessment
L_ext	Extended lifetime
L_exp	Expected lifetime
MCS	Monte Carlo Simulation
M_part	Mass of replacement Part
PLA	Polylactic Acid
PP	Poly Propylene
Replace	product Replacement – one of the RtPFs
RP(s)	Replacement Part(s)
RQ	Research Question
RtPF(s)	Response(s) to Product Failure(s)
SA	Sensitivity Analysis
UPT	Unit Process Table

1. Introduction

Discarded electrical and electronic equipment (EEE) is one of the fastest-growing waste streams globally, driven by shorter product lifetimes due to rapid technological advancements and planned obsolescence (Maitre-Ekern & Dalhammar, 2016). At the same time, studies suggest that our linear economy, based on constant growth, is inevitably reaching the finite limits of Earth's resources (Jackson, 2009). The Circular Economy (CE) offers a viable alternative by fundamentally reshaping how we think about production and consumption (European Commission, 2020). The CE emphasizes a systematic shift to circular design, prioritizing strategies like reuse, repair, remanufacturing, and recycling (Ellen MacArthur Foundation, 2015).

Shorter product lifetimes contribute to premature disposal of products that could otherwise be repaired (Satyro et al., 2018). Repair is a key strategy within the CE, helping to reduce environmental impacts through product lifetime extension and waste reduction (Bocken et al., 2016). Recognizing these benefits, the EU's 'Right to Repair' directive (COM/2023/155 final, 2023) promotes spare part availability and repair-friendly design, while grassroots movements like the Repair Café Foundation (Open repair, n.d.) empower individuals to repair their own products. However, barriers persist, such as expensive replacement parts (RPs), limited availability of RPs and high repair costs (Sabbaghi et al., 2016). Repair, and its effect on reducing environmental impacts, has been a topic of research (Bovea et al., 2020; Sandez et al., 2024). To fully understand the environmental trade-offs of repair and compare it with other end-of-life strategies, a structured and quantitative approach is required.

One such approach is Life Cycle Assessment (LCA), a widely used method for evaluating the environmental impacts of products or services from raw material extraction to disposal. By analyzing economic and environmental flows, LCA provides qualitative potential environmental impacts data that could inform environmentally sustainable decision-making in both industry and policy (Finnveden et al., 2009). However, LCA serves as a decision-support tool rather than a definitive solution, requiring careful interpretation and possibly integration with other methodologies to inform sustainable decision-making (Bruijn et al., 2006). Standardized under ISO 14040 (International Organization for Standardization, 2006), LCA involves four key steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1). The process is inherently iterative, requiring ongoing refinement of the scope, goals, and parameters to incorporate new data and insights as they arise (Bruijn et al., 2006).

LCA provides a structured framework for evaluating the environmental impact of additive manufacturing (AM), commonly known as 3D printing. AM has gained attention as a potential alternative to conventional manufacturing by building components layer by layer instead of material removal used in conventional machining. Through this approach, it enables the creation of complex geometries, reduces initial costs (Gouveia et al., 2022), and supports mass personalization and decentralized production (Attaran, 2017). While often considered a novel method, AM has already been widely adopted in specialized applications, including rapid prototyping (Huang et al., 2016), custom tool fabrication (Navah et al., 2023), and medical implants (Ahangar et al., 2019).

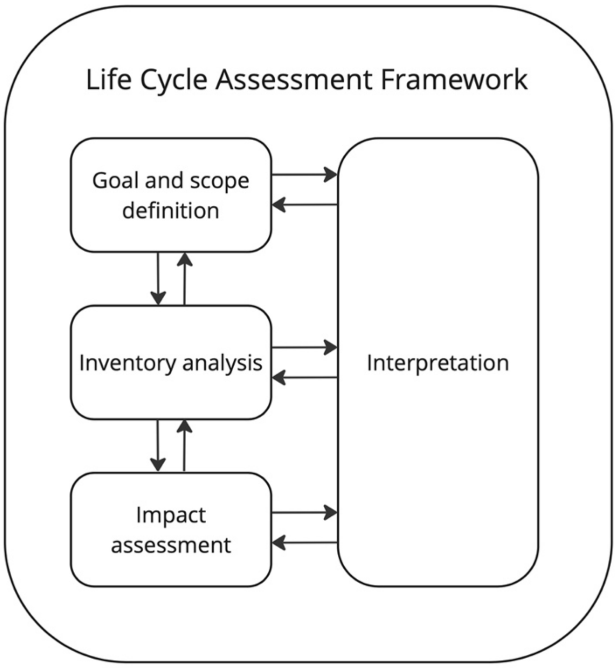

Figure 1: ISO 14040 framework, adapted from (International Organization for Standardization, 2006)

On the one hand, qualitative research has explored how AM can contribute to sustainable design strategies (Sauerwein et al., 2017), such as lightweight design (Matsumoto et al., 2017), part consolidation (Yang et al., 2019) and improved product repair (Graziosi et al., 2024; Van Oudheusden et al., 2023). Nontheless, these studies lack quantitative environmental impact analysis, making it difficult to validate the actual sustainability benefits. On the other hand, LCA studies have quantitatively assessed direct environmental impact of AM (Faludi et al., 2015; Garcia et al., 2021; Kokare et al., 2023; Van Sice & Faludi, 2021). Generally, AM tends to have a greater environmental impact compared to conventional manufacturing methods - such as injection molding (IM) - due to high energy consumption (Faludi et al., 2017; Ford & Despeisse, 2016; Van Sice & Faludi, 2021). However, these LCA studies are highly context-dependent (Graziosi et al., 2024). Sauerwein et al. (2019) suggest that AM's environmental assessment should extend beyond the process parameters to a more systematic level assessment, where the full potential of AM in sustainable design can be accurately and quantitatively evaluated. However, this is challenging due to the context-specific nature of such assessments.

The extant literature highlights AM as a valuable tool in repair processes (Graziosi et al., 2024). Samenjo et al. (2021) estimated that 7.5-29% of failed consumer repairs could benefit from AM, while Chekurov & Salmi (2017) found that repair lead times could be reduced from 14 to 3 days by streamlining product chains with 3D printing. The use of AM in repair generally follows one of two strategies (Sauerwein et al., 2019). First, as an alternative to conventional supply chains through on-demand production, reducing inventories by producing parts as needed (Ford & Despeisse, 2016; Huang et al., 2016). Second, as a means of producing unavailable spare parts when original manufacturers no longer supply them (Chen et al., 2015; Matsumoto et al., 2017).

One of the main challenges of the application of AM for repair, as identified by Oudheusden et al. (2023), is the digitalization of spare parts. Designing a functional RP requires multiple iterations of physical printing, testing for mechanical fit and functionality, and redesigning before the part is ready for use. To this end, Oudheusden et al. (2023) developed the 3D Printing for Repair (3DPfR) framework, which systematically guides the use of AM to produce spare parts for repair but also highlights the iterative nature of the design process. Their work served as the foundation for the '3D Printing Repair Guide' (Arriola et al., 2022) for consumer AM repairs.

Problem Statement

The environmental impact of AM in consumer-electronics repair is underexplored. While AM offers sustainable repair potential, its environmental impact per part is higher than conventional IM. Additionally, the digitalization of repair processes involves multiple testing and printing iterations, increasing its environmental footprint. This raises critical questions about under what conditions AM-enabled repair can be considered environmentally sustainable.

Knowledge Gap

Despite growing interest in AM as a tool for repair, current life cycle assessment studies fail to fully assess its environmental impact in the context of a repair ecosystem. Most studies focus either on isolated parameters or emphasize qualitative approaches like AM-enabled sustainable design strategies. Few, if any, studies adopt a systematic and quantitative perspective that evaluates AM-enabled repair within the broader context of a product life cycle. This gap leaves significant uncertainties regarding the environmental trade-offs of AM compared to conventional repair techniques.

Research questions

This study aims to address the above-stated problem by exploring the identified knowledge gap in the extant research through the following research questions (RQs):

- *RQ1: What variables and scenarios are relevant for assessing the impact of AM in the context of a repair ecosystem?*
- *RQ2: What are the key drivers of significant variations in the environmental impact of AM-enabled repair?*
- *RQ3: Under what circumstances is one response to product failure favorable over another?*
- *RQ4: What actionable insights can be drawn from this study about the application of AM for repair compared to alternative responses to product failure?*

Relevance of the Study

This study addresses the existing knowledge gap by examining AM's environmental impacts on consumer product repair through a case study approach of a Senseo HD6569/00 coffee machine (CM). Using LCA methodology, this study quantifies the environmental effects of various AM-based repair methods, providing data-driven insights to identify unsustainable repair practices. Furthermore, the research offers nuance to the discussion on AM's potential environmental benefits while also laying a foundation for future studies on AM as a product repair strategy.

2. Methodology

A research approach for this study is presented in Figure 2. It's based on the ISO 14040 framework (International Organization for Standardization, 2006) for LCA, but the afore mentioned research questions are placed to its corresponding LCA phase. All boxes are connected with bidirectional arrows, representing the iterative nature of LCA.

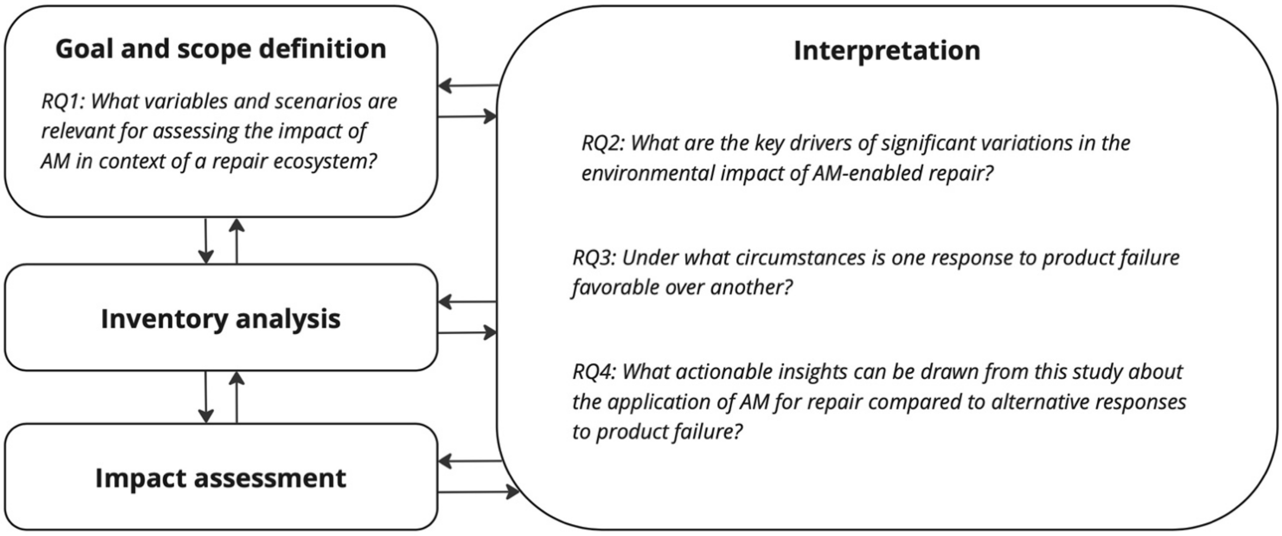

Figure 2: research diagram displaying the approach for this study, including its corresponding research questions. Based on the ISO 14040 framework (International Organization for Standardization, 2006).

This study adopts a case study design to provide the high context dependencies necessary for conducting a robust LCA (Graziosi et al., 2024). The Philips Senseo HD6569/00 CM is selected as the representative product (Figure 3). Philips is one of the most repaired brands in repair cafés, with CMs and other kitchen appliances ranking among the most frequently repaired product categories (Samenjo et al., 2021). Additionally, the Philips Senseo CM has been the object of prior research, such as (Oudheusden et al., 2023).

Variable selection

Among similar LCA studies on repair of EEE, a wide range of variables are investigated, reflecting differences in focus and research objectives. Appendix D: 'Variable selection' presents an overview of variables used in literature based on a review by Sandez et al. (2024). Additional information on the variables used in this research can be found here. Furthermore, the appendix concludes that a common denominator in literature is the inclusion of lifespan extension as a variable, along with multiple responses to product failure, such as repair or replacement.

This study's main goal is to provide a deeper understanding of the environmental impacts of AM in the context of repair. Lifespan extension is a crucial variable as it makes the environmental impacts directly dependent on the product's lifespan. Similarly, including multiple repair responses and techniques enhances the study's validity by capturing a broader range of repair scenarios. Additionally, part weight is identified as a key variable due to its strong correlation with AM-related factors such as printing time, energy consumption, and filament usage (Kokare et al., 2023). These factors significantly influence the environmental impact of the 3D printing process, making part weight a critical consideration in assessing AM-enabled repairs. Although this variable is not mentioned in the literature, it is considered critical to answer the questions of this study. While many of the reviewed studies include more than three variables, this study is limited to three—lifespan extension, repair technique, and part weight due

Figure 2: Philips Senseo HD6569 coffee machine (Philips, n.d.).

to time and resource constraints. In the following section, these three variables are briefly presented.

Expected and extended product lifetime

The ‘expected life’ span for a CM is set at six years, based on the work of (Bovea et al., 2020; Hicks & Halvorsen, 2019). A product failure is assumed to occur after those six years. After this product failure, a repair extends the lifespan a maximum of another six years, referred to as the "extended lifetime". Despite the generally reduced mechanical performance of AM parts (Lay et al., 2019), this study assumes that the production method does not affect product lifespan for reasons of simplification. Furthermore, it assumes only a single repair is carried out during the product's lifetime.

Part mass

This variable represents the mass of the replaced part, ranging from 11 to 177 grams, as determined through disassembly. However, this range serves as a reference, as the variable remains dynamic within the LCA model. For consistency, this study assumes identical part weights for both AM and IM RPs, fulfilling the same function.

Response to Product Failure

Response to product failure (RtPF) describes the approach taken to address product failure at the end of the expected lifespan. Table 1 describes all RtPFs used in this study, their iterations as well as their appearance - or lack thereof - in the research literature.

LCA model

LCA is the method of choice for this study for the following reasons. Firstly, LCA provides a holistic and systematic approach that can incorporate an entire repair ecosystem from cradle to grave. Secondly, LCA is specialized in producing quantitative environmental data of a specific product or system over a selected substance or group of substances. Thirdly, LCA is capable of directly comparing multiple alternatives by means of the same unit of measurement, also known as a functional unit (Bruijn et al., 2006). While LCA offers these significant advantages, some limitations must also be acknowledged. For instance, it struggles to address localized impacts due to its lack of a framework for site-specific risk assessments (Tam et al., 2022) or dynamic, time-dependent analyses (Levasseur et al., 2010). Despite these challenges, LCA remains a robust and well-suited methodology for assessing the environmental impacts of AM-enabled repair in this study.

Goal and scope

The goal of this LCA is to quantify the environmental impacts of AM in the context of repair and to compare these to alternative RtPFs. It aims to prevent unsustainable practices in product repair settings by producing quantitative environmental impact data. The results of this LCA are intended for academic research purposes only. This study is an attributional LCA, as it only focusses on the environmental impacts directly associated with the modelled life cycle stages. No broader system changing decisions are considered (Sonnemann & Vigon, 2011). The boundary of this study is a cradle to grave analysis of a Philips Senseo HD6569/00 CM.

Outside of the system boundary are resources consumed during the CM's use phase, such as electricity, coffee, and cleaning agents. The rate of consumption of these consumables is assumed to remain stable, regardless of whether the machine is repaired or replaced. Printer heat up time is neglected, as it is mere minutes for the selected printer (Ultimaker, n.d.-b). Printer Idle scenarios are not included, as an earlier SA concluded this factor is minimal (Appendix C: BASE_MODEL_1). A global market is assumed for raw material sourcing. Fabrication of sub-assemblies is assumed to be within Europe whereas the final assembly is in Poland. From thereon, a geographical scenario for logistics is developed, based on real world data. Repair and disposal stages are set in the Netherlands. The study assumes a present-day technology mix and most recent available data sources are used in this study.

Functional unit and alternatives

The function of a CM is to provide a mean of producing coffee for consumers in the Netherlands. The functional unit (FU) is defined as *‘provide a year of coffee machine use for a consumer in the Netherlands.’* Each of the five RtPF(s) is an alternative of this FU as is displayed in Table 1.

Life cycle inventory

The following subchapter briefly describes how the LCA model is created, including model assumptions and decisions for the life cycle inventory.

Table 1: Response to product failure (RtPF) description and alternative.

RtPF	Description	Alternative *"Provide a year of CM use for a consumer in the Netherlands through a CM…*
Replace	the CM is fully replaced with a new identical model after failure at the end of its expected lifespan. (Sandez et al., 2024).	…that is *replaced* with an identical machine when a part fails at the end of its six-year life span."
IMRP	Assumes failure at the end of the product's expected lifespan, extended through repair using an IM RP, including logistics from factory to consumer. (Sandez et al., 2024).	… where a part with a mass of [part weight] fails after six years, but *is repaired with an injection molded replacement part*, leading to an extended lifetime of [lifetime extension] years."
IMRP-*n*	Assumes failure at the end of the product's expected lifespan, extended through repair using an IM RP, including logistics from factory to consumer. Overproduction of 2, 5, and 10 IM RPs is included, which are stored and then discarded.	… where a part with a mass of [part weight] fails after six years but *is repaired with an injection molded replacement part as well as overproducing [n] replacement parts*, leading to an extended lifetime of [lifetime extension] years."
AMRP	Assumes failure at the end of the product's expected lifespan, extended using an AM-ready RP. A pre-digitalized model allows on-demand printing at the required location and time. Once printed, the part is installed like a conventional RP. The potential of AM for on-demand repair is highlighted by Ford & Despeisse (2016) and Sasson & Johnson (2016).	… where a part with a mass of [part weight] fails after six years, but *is repaired with AM-ready replacement part,* printed on an Ultimaker 5S+ running for 1500 hours / year and a lifespan of five years; leading to a CM lifetime extension of [lifetime extension] years."
AMRP-*n*	Assumes failure at the end of the product's expected lifespan, extended through design of AM RP using"3D Printing for Repair" guide (Arriola et al., 2022). Data on this iterative process design iterations is scarce, with Oudheusden et al. (2023) providing two data points. Based on this, the study assumes 2, 4, 6, 8, or 10 design iterations before the part is sufficient.	… where a part with a mass of [part weight] fails after six years, but *is repaired with an AM replacement part, designed using the 3DPfR framework in [n'] design iterations*, printed on an Ultimaker 5S+ running for 1500 hours / year, and a lifespan of five years; leading to a CM lifetime extension [lifetime extension] years."

Cut-offs

The following processes are cut off from this study as they are not the primary focus and thus are excluded due to time and resource constraints:

- Modelling of the CM is simplified, although explicit data is available through the disassembly process.
- Post-processing from AM parts is excluded.
- Emissions related to the actual repair process of the CM are excluded, such as repair tool use.
- End of life is modeled as a single background process, despite the existence of a sophisticated electronics recycling system in the Netherlands.

Data collection

This section briefly describes how data is collected for the LCA model. Appendix 'Supplementary_data_A' and 'Supplementary_data_B' include a unit process table (UPT) containing the exact data per process used in the model. Furthermore, Table 2 briefly highlights important variables used in the model as well as their appendix reference. The bill of materials (BOM) for the CM is derived from disassembly (n=1) and supplemented with grey literature. Transport logistics for the CM are based on a hypothetical transport scenario. Environmental impact for warehousing is based on (Fichtinger et al., 2015), with a warehousing period of six months assumed. Corrugated box weights are scaled using a linear formula relative to part weight. The selected printer in this study is the Ultimaker 5+ using poly Lactic Acid (PLA) as filament. This combination is common in public maker spaces and is in line with Oudheusden et al. (2023). The Ultimaker 5S+ BOM is loosely based on Faludi et al. (2015) and (Ultimaker, n.d.-a) and is validated by a SA of an earlier LCA model iteration (see appendix C: BASE_MODEL_1). Print speed is based on primary data collection (n=13). In order to improve geographical accuracy, some major production processes are made into foreground processes (e.g. metal production and PP production). All background process data is provided by the Ecoinvent database version 3.9.1.

Model implementation

The LCA model consists of three sub-models (i.e. product systems): (1) coffee machine production, (2) injection-molded replacement part production, and (3) 3D printing of the replacement part. The environmental impact for each individual sub-model is calculated in OpenLCA 3.2, employing ReCiPe 2016 (Hierarchist) midpoint as the Life Cycle Impact Assessment method. Each sub-model also includes its corresponding end-of-life impacts. Then the output of these sub-models is combined using excel to calculate the environmental impact for a given RtPF, part mass and lifetime extension. The combining of these models is done according to, equation (1) to (5) in appendix Supplementary_data_A contains these calculations.

Flow chart

The flow charts for this model can be found in appendix J: Flow charts. In this appendix, Figure I to Figure K display three sub-systems used for environmental impact calculation as described in the main report. Figure L displays the entire model, used for Monte Carlo Simulation (MCS). In addition, the flow charts are attached as separate files to this report.

Table 2: key variables used in the LCA model.

Name	Description	Value	Unit	Source
Printer build speed	Amount of material deposited in one hour	0.00787	kilograms / hour	Primary data collection (n=13). See appendix E.
Printer use scenario	Use scenario of printer utilization.	1500	Hours / year	Assumption based on (Faludi et al., 2015), validated through SA in Appendix C.
Printer lifespan	Functional lifespan of printer before end of life.	5	years	Assumption based on (Faludi et al., 2015), validated through SA in Appendix C.
Printer power consumption	Average electricity consumption of printer.	0.3	kWh	Number provided by manufacturer (Ultimaker, n.d.-b).
Printer waste	Share of waste in relation to part weight. E.g. discarded prints, supports etc.	21	%	Assumption based on average of literature review by (Kokare et al., 2023), SA in Appendix C.
Transport	(hypothetical) scenario of transport.	1869*	km	Route based on known starting location and end country, mid-points filled in with a hypothetical scenario. Distance based on Google Maps. See Appendix F.
Warehouse building use	Accounted share of 'warehouse building use' per parcel unit.	41.157E-05	m2	Calculation data based on (Fichtinger et al., 2015). See Appendix G.
Storage energy consumption	Average energy consumption for warehouse package handling.	0.28036	kWh	Calculation data based on (Fichtinger et al., 2015). See Appendix G.
Bill of materials Philips Senseo HD6569/00 CM.	Mass-based bill of materials of CM, sorted by material and subassembly.	2482*	grams	Product disassembly (n=1). See Appendix H.
Bill of materials Ultimaker 5S+	Assumed mass-based bill of materials for Ultimaker 5S+.	20600*	grams	Assumptions based on (Faludi et al., 2015; Ultimaker, n.d.-a). Results validated through SA. See Appendix C & I.

* This number is presented in this table as a sum of multiple processes.

Data quality and uncertainty

In order to assess the data quality of all foreground processes, the built-in Ecoinvent data quality assessment Pedigree matrix is used. Decisions present in the matrix are based on expert judgement and the per-process results are included in Supplementary_data_A. Then MCS is used to obtain model uncertainty (Bruijn et al., 2006). Due to erroneous uncertainty data present in the Ecoinvent database, a MCS is only run for the foreground processes using 2000 runs. Appendix K: Model uncertainty further discusses the erroneous Ecoinvent uncertainty data, MCS implementation as well as the number of MCS runs.

3. Results

The second RQ, '*What are the key drivers of significant variations in the environmental impact of AM-enabled repair?*', is answered at two levels. First, at the sub-model level, hotspots are identified through a CA. Then, at the product-system level, the effect of input variables and system dynamics is reviewed through a SA of the variable 'RtPF'. Before addressing RQ3, the criteria for determining when an RtPF is considered 'favorable' over another are established. RQ3 asks: '*Under what circumstances is one response to product failure favorable over another?*'. To answer this, a repair technique break-even chart is introduced to illustrate the break-even boundaries for different RtPFs. Additionally, a scenario evaluation tool is introduced to provide further insights into these break-even points. Finally, the following conclusion chapter synthesizes these findings to answer RQ4: '*What actionable insights can be drawn from this study about the application of AM for repair compared to alternative responses to product failure?*'

Contribution analysis

In order to find key drivers of environmental impact on a sub-model level, a CA is performed in Figure 4 & Figure 5.

Figure 4: Contribution Analysis of sub-system 'production of 1 coffee machine'. Contribution for selected or accumulated processes, over each impact categories. All results scaled relatively.

Figure 4 displays the CA of the subsystem 'production of one coffee machine.' Although the printed circuit board (PCB) accounts for only about 1% of the total weight of the CM, it is a major contributor to most impact categories. The majority of these impacts can be traced back to gold smelting and refining, used for electrical conductivity in the PCB. Another significant hotspot is copper production, including the 66% copper content in the power cable, where environmental impacts primarily stem from copper smelting.

Figure 5: Contribution Analysis of sub-system '1 kg of 3D printed replacement part' and '1 kg of injection molded replacement part'. Contribution for selected or accumulated process, over each impact categories. Results scaled to the greatest impacting sub-system per impact category.

The two sub-systems displayed in Figure 5 can be directly compared, as their unit is 'per 1 kg of produced replacement part'. In the IM process, 'Logistics' refers to the transport of the RP from the factory gate to the consumer. This process includes truck transport, cardboard box packaging and filler material, as well as warehouse building impact and electricity consumption for HVAC, HMME, and lighting during warehouse storage. A storage time of six months is assumed. For AM, the electricity consumption from the process 'Electricity for 3DP' is entirely used for filament extrusion into a RP. It can be observed that the production of 1 kg of RP using AM has a greater environmental impact across all impact categories (ICs) compared to IM. Three main factors contribute to this difference: 'electricity for 3DP', '3D printer production' and a higher raw material impact for 'polylactic acid (PLA) production' in comparison to 'poly propylene (PP) production'.

Sensitivity analysis

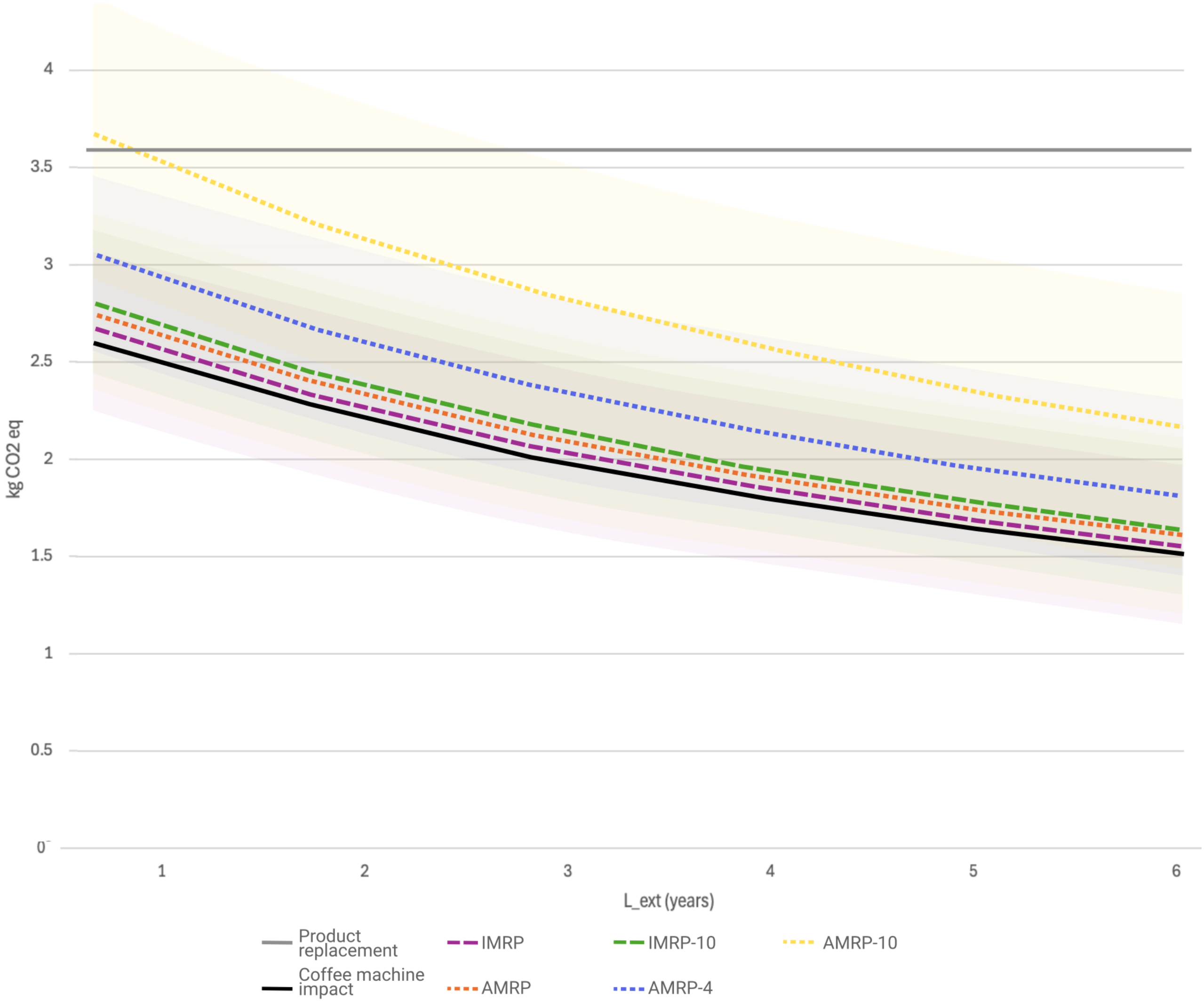

Figure 6: Sensitivity analysis of the variable RtPF displaying the kg of CO2-eq. per year of coffee machine use. The figure displays selected RtPFs over the lifetime extension (L_ext) in years. For this figure, part mass is fixed at 20 grams and impact category 'Global warming' is selected. The uncertainty, highlighted by semitranslucent coloring, covers 95,6% of the data points (μ ± 2σ).

The sensitivity of RtPF is displayed in Figure 6 through the comparison of five selected RtPFs, each evaluated for a fixed part mass and IC. In addition, the 'Coffee machine impact' line is included, representing the fixed impact of CM production, which is part of, and remains constant across, all RtPFs. Each line represents mean values, while the semi-translucent shading indicates the corresponding uncertainty range of ± 2σ, capturing 95.6% of the data points. The aim of Figure 6 is to highlight the sensitivity of the variable RtPF, allowing for a comparison of the environmental impact of different RtPFs over a product's lifetime extension. For example, injection molding without overproduction (IMRP), which extends product life by only one year, has the same carbon footprint as 3D printing for repair with ten printed part iterations (AMRP-10), which extends the product life by four years.

Break-even chart

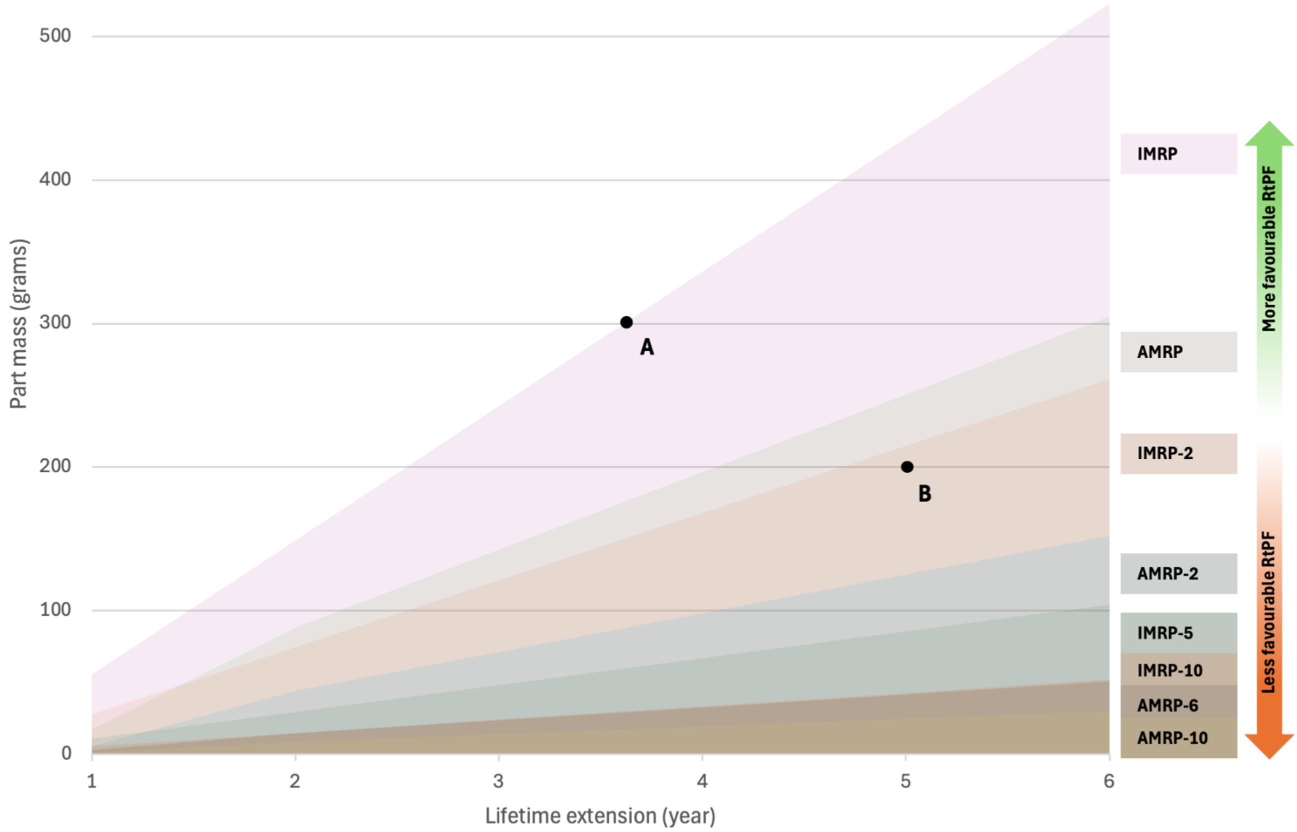

Figure 7: RtPF break-even chart. This chart depicts the environmental Break-even values of part mass and lifetime extension for selected repair-based RtPFs in comparison to product replacement. Break-even is achieved when an alternative has a lower environmental impact in ALL impact categories compared to product replacement (including uncertainty).

Figure 7 illustrates the lifetime extension and part mass thresholds at which each repair method becomes environmentally preferable to product replacement. A break-even point occurs when a specific RtPF has a lower environmental impact than product replacement across all impact categories, including uncertainty considerations (see Discussion chapter). The highlighted areas in the figure indicate where one or more RtPFs achieve break-even. For example, injection molding without overproduction becomes environmentally preferable to replacement for a part mass of 300 grams and extended lifetime by more than 3.5 years (see point A). In contrast, AMRP with 10 printed iterations is only beneficial if the part weighs less than 50 g and extends product life by over six years. Another example is point B, with a part mass of 200 grams and a lifetime extension of five years, IMRP, AMRP, and IMRP-2 have all reached break-even, making them environmentally preferable to product replacement. The other RtPFs, however, have not. Among these, IMRP is the most favorable, followed by AMRP and IMRP-2, as its break-even occurs at a higher part mass. The relative favorability of RtPFs is indicated by the arrows in the figure. Notably, it can be observed that the break-even areas for 'IMRP-10' and 'AMRP-6' almost overlap.

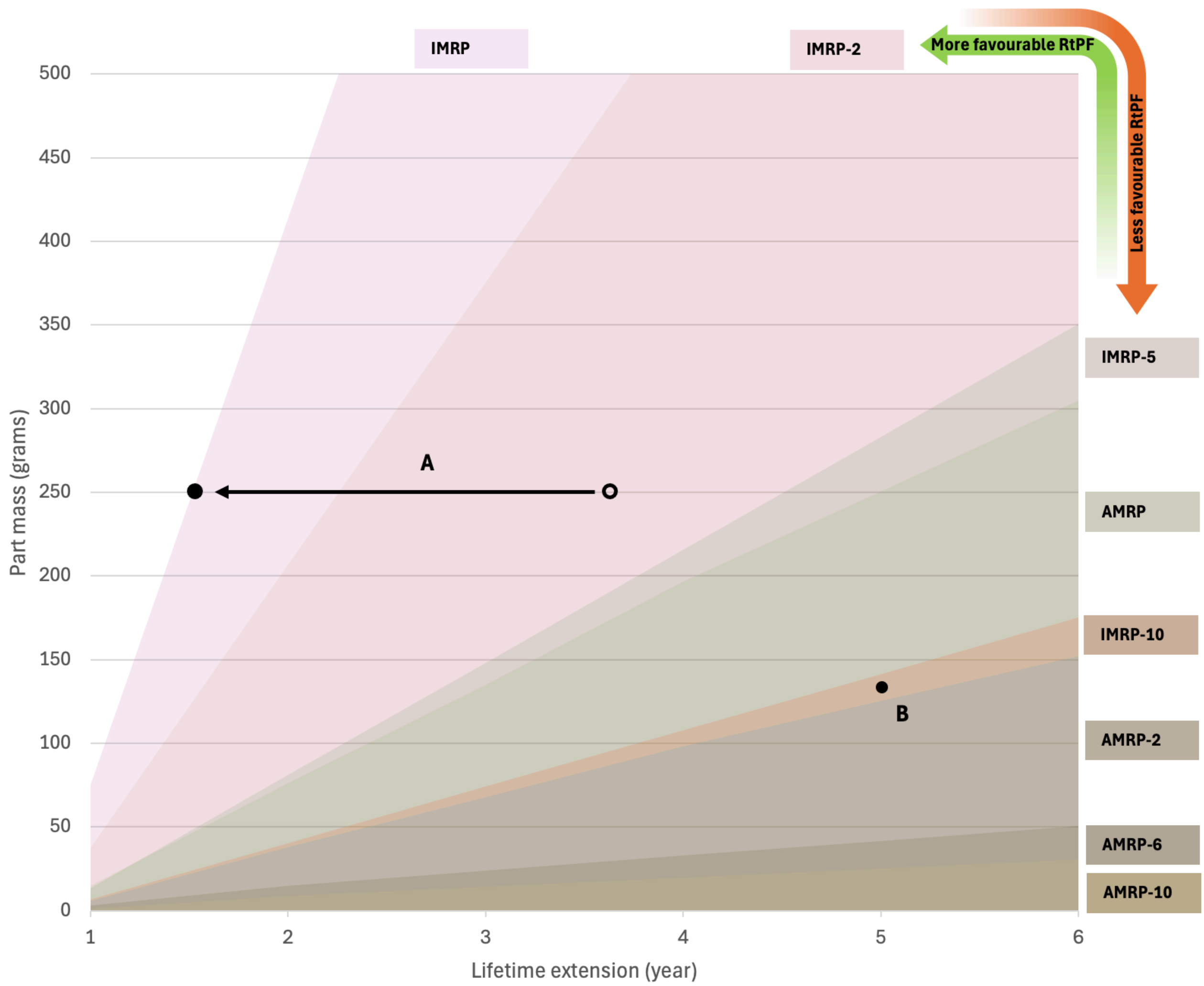

Figure 8: Identical graph as figure 7, only the impact category 'land use' is excluded in the break-even comparison to product replacement. Both figures have similar axis. This chart depicts the environmental Break-even values of part mass and lifetime extension for selected repair-based RtPFs in comparison to product replacement. Break-even is achieved when an alternative has a lower environmental impact in all impact categories except 'land use', compared to product replacement (including uncertainty).

Figure 8 differs from Figure 7 only in that the impact category "land use" is excluded from the break-even comparison with product replacement. The X and Y axis scaling remain unchanged, as a +500 gram replacement part is assumed to be rare. As indicated by Point A, injection molding without overproduction becomes environmentally preferable to replacement for a part mass of 300 grams, with an extended lifetime of six months instead of 3.5 years, as described in Figure 7. At Point B, it can now be observed that all IM-based repairs are environmentally favorable compared to replacement, whereas all AM-based repairs with two or more iterations are not.

Scenario Evaluation Tool

In order to provide a context-specific answer to RQ3, an interactive Scenario Evaluation Tool (SET) was developed (See Supplementary_data_A). It takes part mass and lifetime extension as input variables and calculates the numerical environmental impact per year for each RtPF across all ICs. Furthermore, it indicates whether a repair is environmentally favorable over product replacement by using color coding for each IC and RtPF. The discussion chapter of this report further elaborates on the definition of 'environmentally favorable' and explains how uncertainty is handled.

	Replace	Injection Molding based repair				Additive Manufacturing based repair					
		IMRP	IMRP-2	IMRP-5	IMRP-10	AMRP	AMRP-2	AMRP-4	AMRP-6	AMRP-8	AMRP-10
Fossil resource scarcity	1.0E+00	5.3E-01	5.7E-01	6.7E-01	8.3E-01	6.2E-01	7.4E-01	9.9E-01	1.2E+00	1.5E+00	1.7E+00
Stratospheric ozone depletion	1.7E-06	8.6E-07	8.9E-07	9.9E-07	1.2E-06	1.2E-06	1.6E-06	2.3E-06	3.0E-06	3.8E-06	4.5E-06
Global warming	3.1E+00	1.6E+00	1.7E+00	1.9E+00	2.3E+00	2.0E+00	2.4E+00	3.4E+00	4.3E+00	5.2E+00	6.1E+00
Fine particulate matter formation	8.6E-03	4.4E-03	4.4E-03	4.7E-03	5.1E-03	4.7E-03	5.0E-03	5.7E-03	6.5E-03	7.2E-03	7.9E-03
Human carcinogenic toxicity	4.4E-01	2.2E-01	2.3E-01	2.4E-01	2.5E-01	2.4E-01	2.6E-01	3.1E-01	3.6E-01	4.0E-01	4.5E-01
Freshwater ecotoxicity	2.1E+00	1.1E+00	1.1E+00	1.1E+00	1.1E+00	1.1E+00	1.2E+00	1.3E+00	1.4E+00	1.5E+00	1.6E+00
Water consumption	3.2E-02	1.7E-02	1.8E-02	2.0E-02	2.4E-02	2.1E-02	2.6E-02	3.7E-02	4.7E-02	5.8E-02	6.8E-02
Ozone formation, Human health	9.4E-03	4.8E-03	5.0E-03	5.5E-03	6.3E-03	5.4E-03	6.0E-03	7.4E-03	8.8E-03	1.0E-02	1.1E-02
Ozone formation, Terrestrial ecosystems	9.6E-03	5.0E-03	5.1E-03	5.6E-03	6.5E-03	5.5E-03	6.2E-03	7.6E-03	9.0E-03	1.0E-02	1.2E-02
Mineral resource scarcity	1.1E-01	5.3E-02	5.4E-02	5.4E-02	5.5E-02	5.5E-02	5.7E-02	6.0E-02	6.3E-02	6.6E-02	7.0E-02
Marine ecotoxicity	2.8E+00	1.4E+00	1.4E+00	1.4E+00	1.5E+00	1.5E+00	1.5E+00	1.6E+00	1.8E+00	1.9E+00	2.0E+00
Human non-carcinogenic toxicity	3.3E+01	1.7E+01	1.7E+01	1.7E+01	1.8E+01	1.7E+01	1.8E+01	2.0E+01	2.1E+01	2.2E+01	2.4E+01
Freshwater eutrophication	3.8E-03	1.9E-03	1.9E-03	2.0E-03	2.1E-03	2.1E-03	2.3E-03	2.8E-03	3.3E-03	3.7E-03	4.2E-03
Ionizing radiation	2.8E-01	1.4E-01	1.5E-01	1.7E-01	2.0E-01	1.7E-01	2.1E-01	2.8E-01	3.5E-01	4.2E-01	5.0E-01
Marine eutrophication	2.1E-04	1.1E-04	1.2E-04	1.4E-04	1.8E-04	1.5E-04	1.9E-04	2.7E-04	3.6E-04	4.4E-04	5.2E-04
Land use	7.9E-02	5.0E-02	6.0E-02	9.0E-02	1.4E-01	5.2E-02	6.5E-02	9.1E-02	1.2E-01	1.4E-01	1.7E-01
Terrestrial acidification	2.1E-02	1.1E-02	1.1E-02	1.2E-02	1.3E-02	1.2E-02	1.3E-02	1.5E-02	1.7E-02	1.8E-02	2.0E-02
Terrestrial ecotoxicity	1.0E+02	5.2E+01	5.3E+01	5.3E+01	5.5E+01	5.4E+01	5.6E+01	5.9E+01	6.2E+01	6.6E+01	6.9E+01

Figure 9 Interactive Scenario Evaluation Tool (SET) displaying the numerical environmental impact per year for each RtPF overall impact categories Color coding is used to assess the repair-based RtPF to product replacement. Green: value + 2σ is lower than replacement - 2σ| yellow: value is within range of uncertainty ± 2σ | red: value - 2σ is higher than replacement + 2σ. (See Figure 10). Input parameters for this figure: 6 years of lifetime extension and a part mass of 152 grams.

4. Discussion

The results offer new insights into the environmental implications of different repair strategies. Results highlight the increased impact of AM compared to IM, the influence of key drivers and environmental break-even points for different RtPFs. The following sections discuss these outcomes, as well as their implications and limitations, in relation to the previously defined RQs.

Key drivers

RQ2, *'What are the key drivers of significant variations in the environmental impact of AM-enabled repair?* is first addressed at the sub-system level through a CA. Hotspots in the production of a single CM are highlighted in Figure 4, while Figure 5 compares the production of 1 kg of RP using IM and AM. This analysis demonstrates that the environmental impact of AM is higher across all impact categories compared to IM per kg of RP. Three primary contributors to this higher impact are identified: electricity consumption during printing, 3D printer production, and greater raw material impact for 'PLA production' in comparison to 'PP production'.

These three contributors are compared to a similar study by Faludi et al. (2015). Despite differences in characterization models, printer utilization scenarios, and printer lifespan assumptions compared to the work of Faludi et al., the most comparable scenario from their study is 'FDM, 100% solid parts, Minimum utilization, Powering off'. Roughly similar distribution of process contribution between electricity use and machine production are observed. However, 'material use' appears significantly lower in Faludi et al.'s results. One possible explanation is the difference in the 3D printer used. Faludi et al. assumed a 420 kg Dimension 1200BST, whereas this study examines a 21 kg Ultimaker 5S+. As a result, the higher impact of machine production, along with increased electricity consumption, may reduce the relative contribution of material use in their analysis. However, due to differences in impact characterization models, no explicit comparison can be drawn.

To further elaborate on the results in Figure 5, PLA production for AM has a higher environmental impact across all categories except 'Fossil resource scarcity.' This exception arises because virgin PP, used for IM, is derived from fossil-based resources. Per kilogram of AM RP, 1.21 kg of filament is consumed (Table 2) due to filament waste from supports and failed prints. However, this waste alone does not fully explain the greater environmental impact of PLA compared to PP. As PLA is a biobased material, its higher environmental impact is largely attributed to crop production (land and water use), Walker & Rothman (2020) conducted a literature review of 56 studies on the comparison of environmental impacts of fossil-based and bio-based polymers. Their main conclusion was that significant variation persists across studies, making it difficult to draw definitive conclusions on the environmental impact of these materials. Thus, comparing the raw material production impact of PLA and PP to other literature is problematic, as results heavily depend on the study chosen. Lastly, IM exhibits its highest impact, relative to AM, in the IC 'Land use.' This peak is primarily linked to the paper/cardboard production used for packaging IM RPs within its logistics chain. Within this process, land use impacts are largely driven by softwood production.

RQ2 can also be answered on a product-system level through a sensitivity analysis. Figure 6 performs this analysis on the variable RtPF. This variable was selected for SA because it represents the main research objective of this study and is central to understanding its system dynamics. Firstly, the SA reveals a relatively small increase for 'IMRP' and 'IMRP-10.' Therefore, the number of overproduced IM RPs is not considered a sensitive parameter. However, when additional 3D printing iterations are introduced ('AMRP' compared to 'AMRP-4' & 'AMRP-10'), the impact related to the repair action significantly increases. As a result, the number of 3D printing iterations is considered a sensitive factor and can be identified as a key driver of environmental impact.

The total environmental impact for each RtPF consists partly of the 'base' impact from 'CM production' and partly of the 'added' impact of the repair action. This dynamic results from how the model is calculated in equations (2) to (5) in appendix B: Model equations. This distinction is visualized in the sensitivity analysis in Figure 6 by presenting the 'coffee machine impact' as well as the total impact per RtPF. The previously discussed contribution a concluded that replacement part production using AM has a significantly larger impact than IM. This explains why the 'added' impact of AM-based repairs is significantly larger than that of IM-based repairs. This difference becomes increasingly pronounced as the number of print iterations and overproduced IM replacement parts increase. Although part mass and impact categories are fixed in Figure 6, these parameters can be adjusted dynamically in Supplementary_data_A. When modifying these variables, the model dynamics can be observed. Part mass has a reinforcing feedback effect on the scaling of RtPFs, with 'coffee machine production' serving as the scaling point. Different ICs lead to variations in the initial magnitude of impact from 'coffee machine production' relative to the RtPF, but overall, the pattern remains consistent with the observations described above.

break-even point

Now that key drivers of environmental impact have been identified and model dynamics explored, an answer can be formulated for RQ3: *'Under what circumstances is one response to product failure favorable over another?'* First, it is necessary to define what it means for an alternative to be environmentally 'favorable' over another. To avoid the subjective weighting of impact categories into a single-point score (Prado et al., 2020), an alternative is deemed 'favorable' in this study if it has a lower impact value across all impact categories compared to another alternative. For this study, an uncertainty range of ± 2 standard deviations, capturing 95.6% of data points, is deemed acceptable. When comparing alternatives, uncertainty is assessed as described in Figure 10.

Given this definition, the concept of a break-even boundary naturally follows—a threshold exists at which one repair-based RtPF becomes more favorable over another. In Figure 7, selected RtPFs are compared to product replacement. The figure visualizes the break-even points were become favorable over product replacement for a given combination of part mass and lifetime extension. When an RtPF has a high break-even point, the more favorable the RtPF is compared to other RtPFs. Therefore, a ranking is indicated in Figure 7 using arrows. It can be observed that the order of this ranking is identical regardless of part mass or lifetime extension. AM-based RtPFs always exhibit a higher environmental impact compared to IM-based RtPFs for given part masses and lifetime extensions, resulting in lower break-even points. This effect is pronounced to the extent that 'IMRP-10' and 'AMRP-6' share an almost identical break-even boundary.

This study deploys the previously defined methods to determine when one alternative is 'favorable' over another. Many studies, such as Faludi et al. (2015), use alternative approaches, including single endpoint impact scores. To provide further insights into how different RtPFs compare, an interactive Scenario Evaluation Tool (SET) was developed. It takes part mass and lifetime extension as inputs and can therefore serve as an extension for Figure 7. With these inputs, the tool calculates the numerical environmental impact per 'year of coffee machine use' for each RtPF and IC. Furthermore, it evaluates how each RtPF performs at the IC level compared to product replacement by color coding its results. Using the SET, the following additional insights are observed.

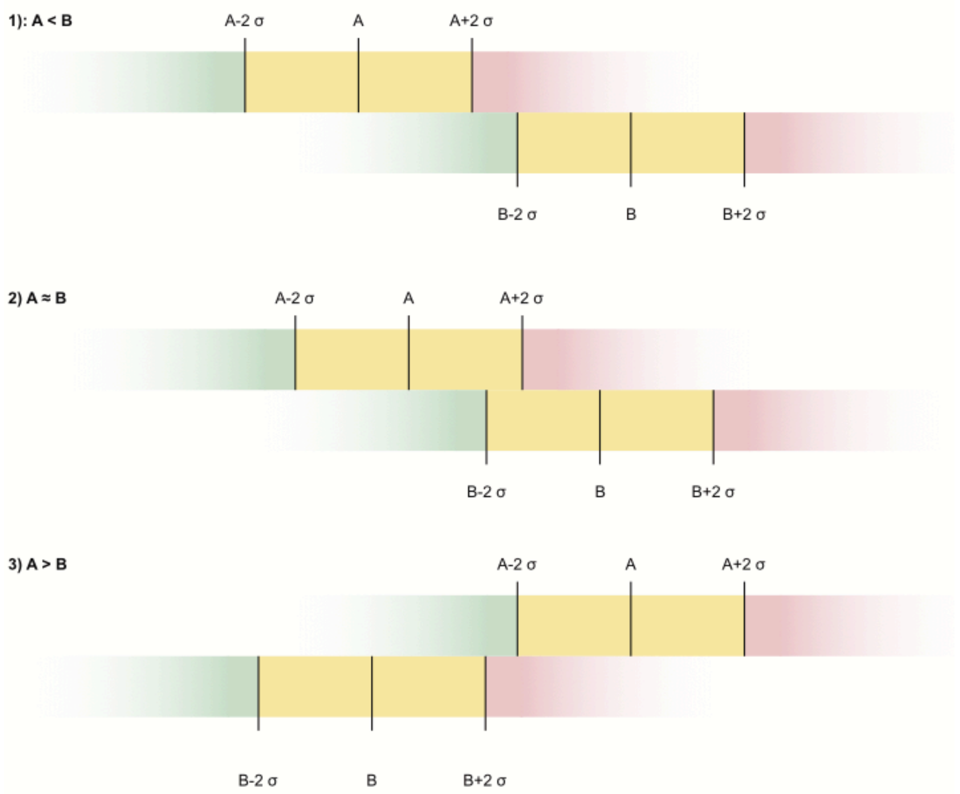

Figure 10: visual representation of comparing expletory alternatives A and B in regard to uncertainty. (1) Alternative A is only considered smaller than B if both alternatives' uncertainty ranges do not overlap. (2) When uncertainty ranges do overlap, comparison A to B is deemed 'uncertain' and is depicted in yellow in Figure 9. (3) Likewise, alternative A is deemed larger than alternative B.

Figure 7 concludes that 'IMRP-10' and 'AMRP-6' have nearly identical break-even points, meaning that both RtPFs exhibit a lower impact score across all impact categories compared to product replacement for a similar part mass and lifetime extension. However, when this scenario is analyzed using SET (Figure 9), it becomes evident that this break-even point for IM-based RtPFs is largely influenced by the high impact of the IC 'land use.' In all other ICs, IM-based RtPFs are 'favorable' over product replacement. The high land use impact is explained in the CA. Figure 5 shows that, relative to AM, IM exhibits its highest impact in the IC 'land use.' A key contributor to this impact is softwood production, which is used in cardboard shipping box manufacturing. If an alternative packaging solution with a lower 'land use' impact was available, it would result in a significantly different break-even point. Based on these findings, a new break-even graph is made that excludes 'land use' when comparing repair to replacement (Figure 8). From this figure it can be concluded that the environmental impacts of IM-based repairs are drastically decreased, see the example of point A in Figure 8. The decrease is to an extend that all IM-based repairs (up to 10 pieces overproduction) have a higher break-even point compared to AM-based repairs with two or more print iterations (AMRP-2). In contrast, in figure 7 this comparison could only be made for AM-based repairs up to six print iterations instead of two (AMRP-6).

Limitations

An inherent limitation of any model is that it provides a simplified representation of reality, which is necessary due to the complexity of real-world industrial, economic, social, and environmental systems (Bruijn et al., 2006). This LCA study is no exception. Therefore, some environmental impacts and system dynamics may not be fully captured in the study results. To account for these model simplifications, uncertainty is introduced. However, due to faulty uncertainty data in the Ecoinvent database, uncertainty in this study could only be assessed for foreground processes using MCS. As this study uses a case study approach, its results are context-specific rather than universally applicable. Variations in the selected CM, 3D printer model, print settings, and transport scenarios—among other factors—could lead to different study outcomes. The same applies to the assessment criteria used in comparing alternatives and define an environmental 'break-even' point. To partially address this limitation, the SET was developed to provide further insights when comparing alternatives. However, the SET is not intended for public or commercial decision-making, as its results are only valid within the context of this study. Further assessment of the Senseo HD6569/00 CM, using the criteria described by Arriola et al. (2022), reveals that only eight parts are suitable for production using AM (see appendix K: Parts of coffee machine feasible for

AM). Nevertheless, the aim of this study is not to repair this specific CM but rather to explore environmental trade-offs between conventional manufacturing and AM in the context of product repair. In this regard, the study successfully achieves its objective.

5. Conclusion

Despite growing interest in additive manufacturing for repair, its environmental impact within a repair ecosystem remains underexplored. Prior life cycle assessment studies focus on isolated factors like energy use or material consumption but miss the broader trade-offs with injection molding-based repair. This case study fills this gap through a systematic assessment of additive manufacturing-enabled repair in consumer electronics.

RQ1: What variables and scenarios are relevant for assessing the impact of AM in context of a repair ecosystem?
Through literature review, three main variables are defined: response to product failure (RtPF), part mass and lifetime extension. RtPF entails the following responses: product replacement (Replace); repair using IM RP (IMRP), including overproduction scenarios up to 10 parts (IMRP-*n*); and repair using AM, based on on-demand production (AMRP) or through up to 10 design iterations (AMRP-*n*). Part mass describes the weight of the failed RP. Lifetime extension refers to the number of years a product's lifespan is prolonged due to repair. A lifetime extension from one to six years is assumed. Based on these three variables, a life cycle assessment is produced.

RQ2: What are the key drivers of significant variations in the environmental impact of AM-enabled repair?
Contribution analysis reveals that additive manufacturing-based repairs consistently have a higher environmental impact compared to injection molding-based repairs in all impact categories. The three main contributors are: high electricity consumption during printing, the environmental impact of producing 3D printers, and the greater impact of polylactic acid in additive manufacturing compared to polypropylene in injection molding. This effect worsens significantly with additional print iterations, making this number a sensitive factor. In contrast, overproducing injection-molded parts has minimal influence on overall environmental performance.

RQ3: Under what circumstances is one response to product failure favorable over another?
To avoid subjective weighting of impact categories, a repair method is considered favorable if it has a lower impact across all categories. This comparison includes an uncertainty range of ±2 standard deviations. The break-even chart (Figure 7) visualizes when repair becomes more sustainable than product replacement based on lifetime extension and part mass. A higher break-even point indicates a more favorable repair option, regardless of part weight or lifetime extension. The analysis shows that injection molding-based repair with ten overproduced parts and additive manufacturing-based repair with six print iterations have nearly identical break-even points. However, the scenario evaluation tool reveals that this threshold for injection molding-based repair is mainly driven by high 'land use' impact from softwood-based packaging. When this category is excluded (Figure 8), the ranking shifts: all injection molding-based repairs become more favorable than additive manufacturing-based repairs with two or more print iterations. This suggests that producing ten injection-molded replacement parts as well as conducting just two additive manufacturing iterations have a roughly identical environmental impact, regardless of part mass and lifetime extension.

RQ4: What actionable insights can be drawn from this study about the application of AM for repair compared to alternative responses to product failure?
This study supports existing research, confirming that injection molding-based repair is the more environmentally sustainable option per replacement part. Consequently, injection molding should always be prioritized for repair when available. However, if no injection-molded replacement part is accessible or available, minimizing the number of additive manufacturing print iterations is crucial, as this is a key driver of environmental impact. Ideally, a single print iteration should be used, as in direct on-demand manufacturing. While this remains less favorable than injection molding-based repair, it is preferable to overproducing two injection-molded replacement parts (or five if 'land use' is excluded).
When neither an injection molded replacement nor an on-demand additive manufactured replacement part is available, a new part can be designed using the 3D Printing for Repair framework. In this case, this study shows that the environmental favorability of product repair over product replacement greatly depends on the number of print iterations required, the part mass, and the assumed lifetime extension achieved through the repair. While the scenario evaluation tool provides insights into these trade-offs, its findings may not be universally applicable due to the context-specific nature of this study. However, if additive manufacturing replacement parts contribute to an open-source, on-demand manufacturing library, their broader sustainability benefits may justify their environmental cost.

Overproduction of injection-molded replacement parts has a smaller impact than the number of additive manufacturing print iterations. In fact, for the same part mass and lifetime extension, producing ten injection-molded replacement parts or performing two to six additive manufacturing print iterations can be more favorable than full product replacement, depending on packaging type.

Research Recommendations

Further research could enhance this case study by conducting a comprehensive uncertainty analysis using monte carlo simulation on its background processes. Expanding the scope beyond a single case study to examine a broader range of 3D printers, printing technologies, and consumer products would improve the study's validity. Additionally, incorporating variables such as repair success rates (Pamminger et al., 2021) and failure types (Bovea et al., 2020) could provide further insights into the environmental implications of AM-enabled repair.

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In writing this report, AI language models were used for the following purposes: finding scientific and grey literature, summarizing literature, clarity and grammar of text written by the author and providing feedback on elements of the work. The language models were used responsibly, and all generated output is thoroughly reviewed in order to maintain academic rigor and originality. The author takes full responsibility for the written work.

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Appendices

A: Supplementary documents

the following supplementary documents are provided with these reports described in Table A.

Table A: supplementary documents provided with this report.

Name	Description
Supplementary_data_A.xlsx	Contains numerical background data for BASE_MODEL_2 as well as the formation of graphs used in this report. Contains: UPT, impact results, contribution analyst, SA, break-even graph, SET
Supplementary_data_B.xlsx	Contains numerical background data for BASE_MODEL_1. This model is referred to in Appendix C: BASE_MODEL_1. Contains: UTP, SA scenarios, sensitivity results.
Flow_Chart_BASE_MODEL_2_EI_3DP	Full size flow chart of 3D printing 1 kg of replacement part
Flow_Chart_BASE_MODEL_2_EI_CM	Full size flow chart of coffee machine production
Flow_Chart_BASE_MODEL_2_EI_IM	Full size flow chart of 3D printing 1 kg of replacement part
Flow_Chart_BASE_MODEL_3	Full size flow chart of BASE_MODEL_3
BASE_MODEL_1 (ecoinvent 9.1).zolca	Earlier OpenLCA model referred to in Appendix C: BASE_MODEL_1
BASE_MODEL_2 (ecoinvent 9.1).zolca	Main OpenLCA model used in report.
BASE_MODEL_3 (ecoinvent 9.1).zolca	OpenLCA model used for MCS as described in appendix K: Model uncertainty.

B: Model equations

The output of each sub-model as calculated in OpenLCA is combined in excel (Supplementary_data_A.xlsx)to calculate the environmental impact for a given RtPF, part mass and lifetime extension. The combining of these models is done according to the following equations.

Equation 1: product replacement (Replace).

$$EI_{tot} = \frac{EI_{cm}}{L_{exp}}$$

Equation 6: repair using injection molded replacement part (IMRP).

$$EI_{tot} = \frac{EI_{cm} + EI_{im} * \ M_{part}}{L_{exp} + L_{ext}}$$

Equation 6: repair using injection molded replacement part including overproduction (IMRP-n)

$$EI_{tot} = \frac{EI_{cm} + EI_{im} * \ M_{part} * n}{L_{exp} + L_{ext}}$$

Equation 6: repair using AM ready RP (AMRP)

$$EI_{tot} = \frac{EI_{cm} + EI_{3dp} * \ M_{part}}{L_{exp} + L_{ext}}$$

Equation 6: repair using 3DPfR designed AM RP (AMRP-n)

$$EI_{tot} = \frac{EI_{cm} + EI_{3dp} * \ M_{part} * n'}{L_{exp} + L_{ext}}$$

Were:
EI_{tot}: Total Environmental Impact (impact / year)
EI_{cm}: Environmental Impact of production of 1 coffee machine (impact)
EI_{im}: Environmental impact of 1 kg injection molded replacement part (impact)
EI_{3dp}: Environmental impact of 1 kg 3d printed replacement part (impact)
n': Number of design and print iterations required before successful print implementation (n)
n: Total number of produced injection molded replacement parts per used replacement part(n)
L_{exp}: Expected lifetime (years)
L_{exT}: Extended lifetime (years)
M_{part}: Mass of replacement part (kg)

C: BASE_MODEL_1

LCA is inherently an iterative process (Bruijn et al., 2006). As this study is no exception, multiple model iterations are produced throughout this study. This appendix briefly describes one of the earlier LCA model (BASE_MODEL_1) iterations and its results, as it is relevant for validating the assumptions upon which the final LCA model is build. Please note the described LCA model below is not the studies final model, but merely an earlier iteration. Only significant details for this model are described here. Additional information can be found in Supplementary_data_B and BASE_MODEL_1 (ecoinvent 9.1).zolca.

Goal and scope

This LCA is a first iteration for this LCA. The aim of this iteration is to get a rough understanding of what to focus on in the definitive LCA as described in the research proposal. This LCA attempts to shed light on the following questions:
-What parts of the model have a major impact on the end results and are thus relevant to further research?
-What parts of the model have a minor impact on the end results and can suffice with little research and/or an assumption?
The rest of the goal and scope is similar as presented in the main report.

Function, functional unit and alternatives.

The following FU and alternatives are defined for this model:
Function: extending the functional lifetime of a consumer coffee machine through conducting a repair.
FU: provide one coffee machine lifetime and one repair.
Alternative 1: provide one coffee machine lifetime and one repair through 3D printing a pre-designed replacement part on a desktop FDM printer in the Netherlands.
Alternative 2: provide one coffee machine lifetime and one repair through designing a replacement part using 3DPfR methodology and printing the replacement part on a desktop FDM printer in the Netherlands.

Figure A provides a graphical overview of the LCA model by means of a flowchart. Some series of background processes are clustered into a single background process for flow chart simplification. Three different 3D printer alternatives are modelled (‘printer alternative 1-3’). Only one printer is used at a time, depending on the model input parameters.

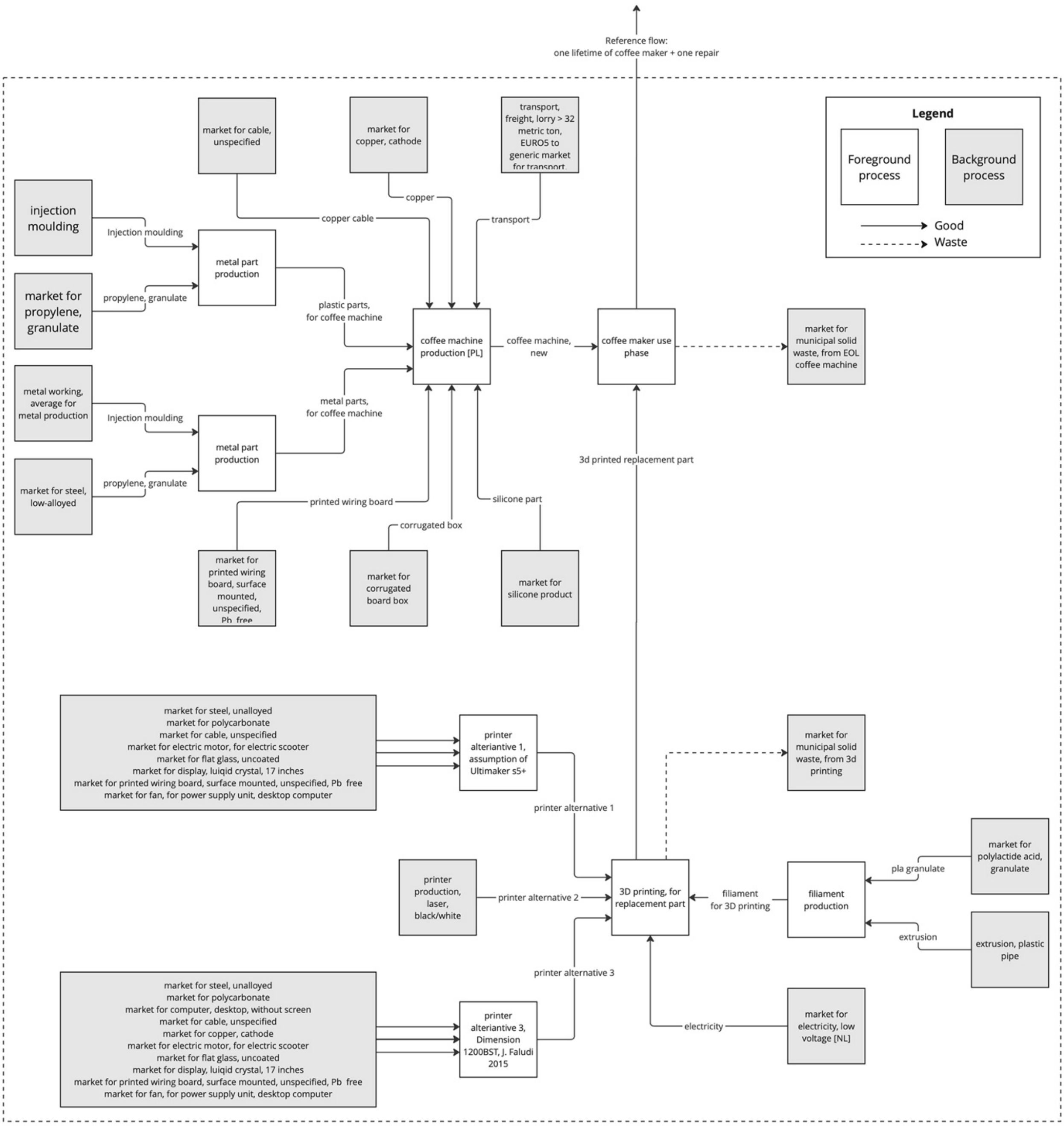

Figure A: Flow chart of previous LCA model iteration BASE_MODEL_1

Sensitivity Analysis

These SA are relevant to validate input parameters in the LCA model, such as 3D printer composition, printer waste and printer lifespan in Table 2. All scenarios and their variations are described in supplementary_data_B. A brief overview of the selected scenarios and their results is provided in Table B. In general, it can be concluded for most variables used in defining the 3D printing process and that therefore these assumptions made in BASE_MODEL_1 could be used in BASE_MODEL_2.

Table B: sensitivity analysis overview of BASE_MODEL_1. Exact scenario description and results further described in Supplementary_data_B.

No.	Analysis	Sensitivity	Recommendation
1.1	Printer composition	Not sensitive	Simplification to use Ecoinvents "market for printer, laser, black/white" as a proxy for Ultimaker 5S+ is acceptable.
1.2	Printer waste (% of print)	Not sensitive	Recommended to gather primary 3dp waste data during 3DP4R process as extra validation.
1.2	Printer waste (3DP4R)	sensitive	Further case study research on iteration cycles and other print waste highly recommended.
1.3	Printer lifespan	Not sensitive	Assumption is acceptable
1.4	Printer usage	Not sensitive	Assumption is acceptable
1.5	Printed part weight	Sensitive	Precisely measure mass of printed part.
1.6	Part production location	Somewhat sensitive	Both regions of RoW and RER include great uncertainty, therefore assumption is acceptable

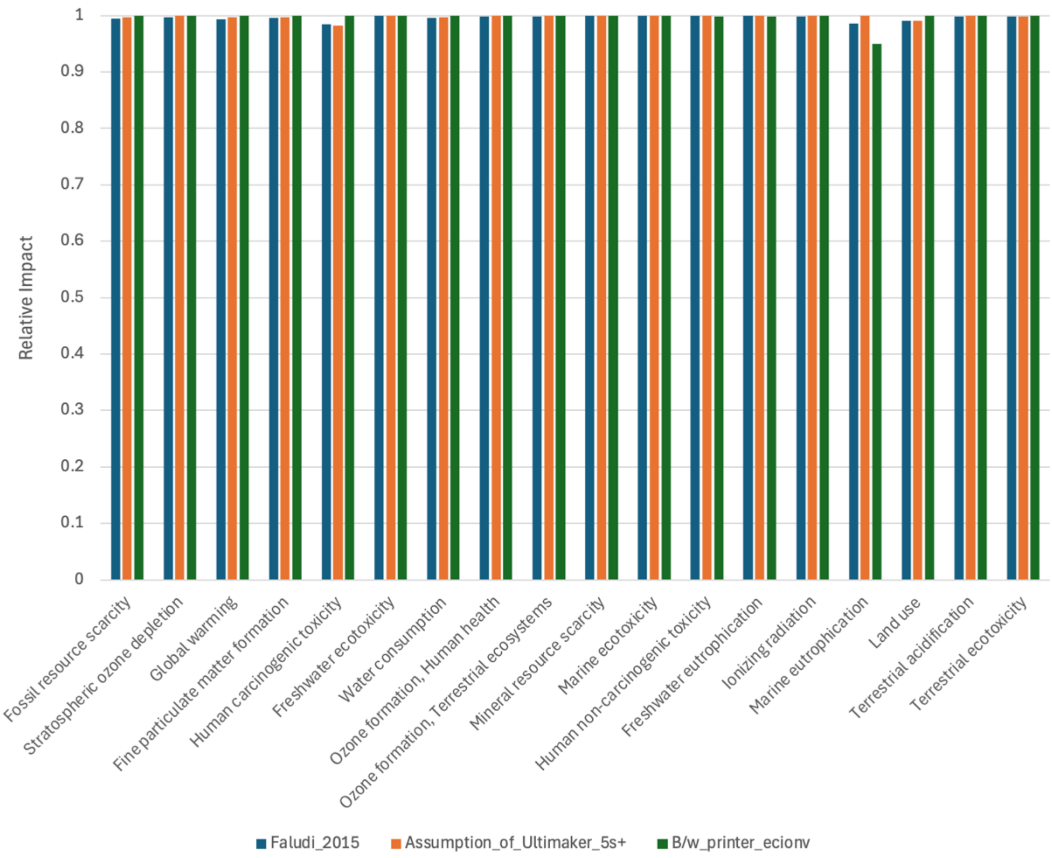

Figure B: Sensitivity analysis on 3d printer composition from BASE_MODEL_1. Results display relative total model output using each of the three printer compositions over all ReCiPe 2016 impact categories. Based on this sensitivity analysis, it is concluded that the exact 3d printer composition is not considered a sensitive variable.

Sensitivity analysis 2: printer waste.

This analysis investigates the effect of different percentages of waste print materials (accounting for failed prints and support material) as described in a literature review by (Kokare et al., 2023). Their results for minimum (9%) and maximum (51%) for FDM 3D printers are included. BASE_MODEL_1 assumes an average of 21% print waste. The relatively large difference in the impact of land use is due to the production of PLA, an agricultural product. Print waste is considered to be not so sensitive as can be seen in Figure C.

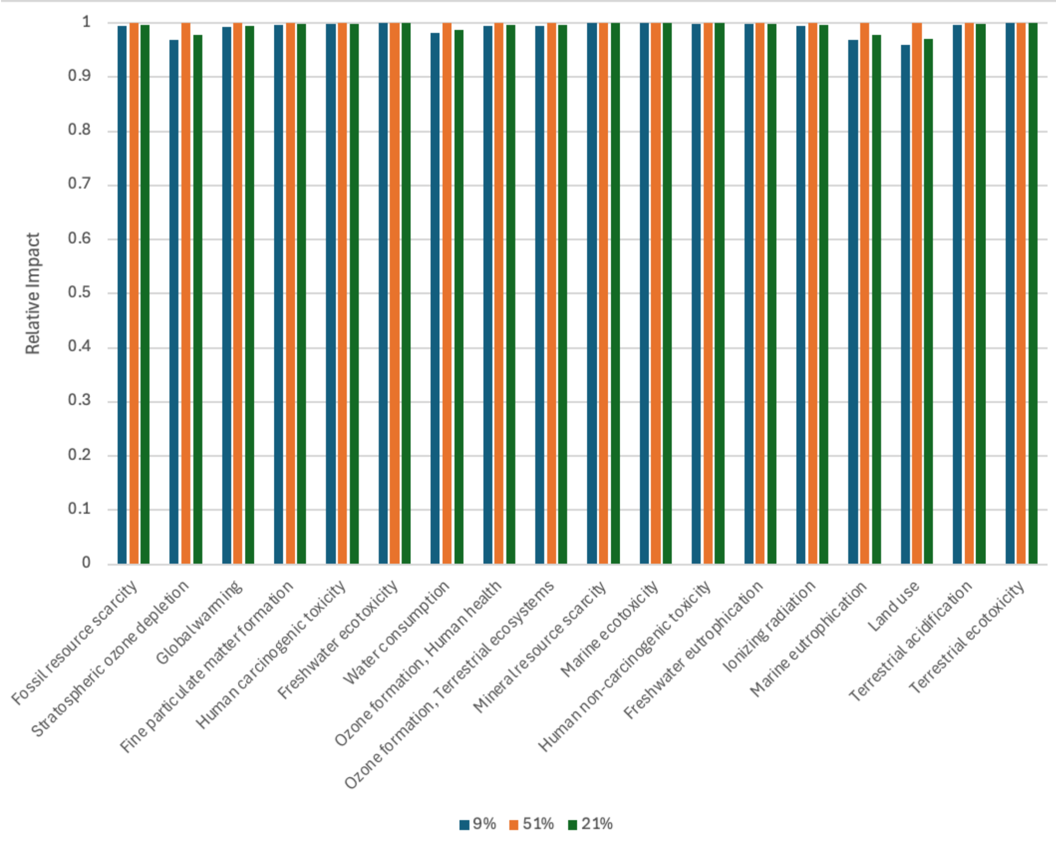

Figure C: Sensitivity analysis on printer waste from BASE_MODEL_1. Results display relative total model output using different ratios of print waste based on (Kokare et al., 2023) over all ReCiPe 2016 impact categories. Based on this sensitivity analysis, it is concluded that print waste is not a sensitive variable.

Sensitivity analysis 3: printer lifespan.

This SA investigates the effect of different 3D printer life spans. BASE_MODEL_1 assumes five years, which is the same assumption made for the 3D printer in (Faludi et al., 2015). Ten years is a high range life span as suggested by the manufacturer the previously mentioned study. two years is added as a low-end assumed comparison. In conclusion: five to years is a more realistic lifespan than just two years as suggested by Faludi (2015). When comparing five to ten years, only one IC is changed more than 1% of the total impact (Figure D). Therefore, this variable is considered to be not sensitive.

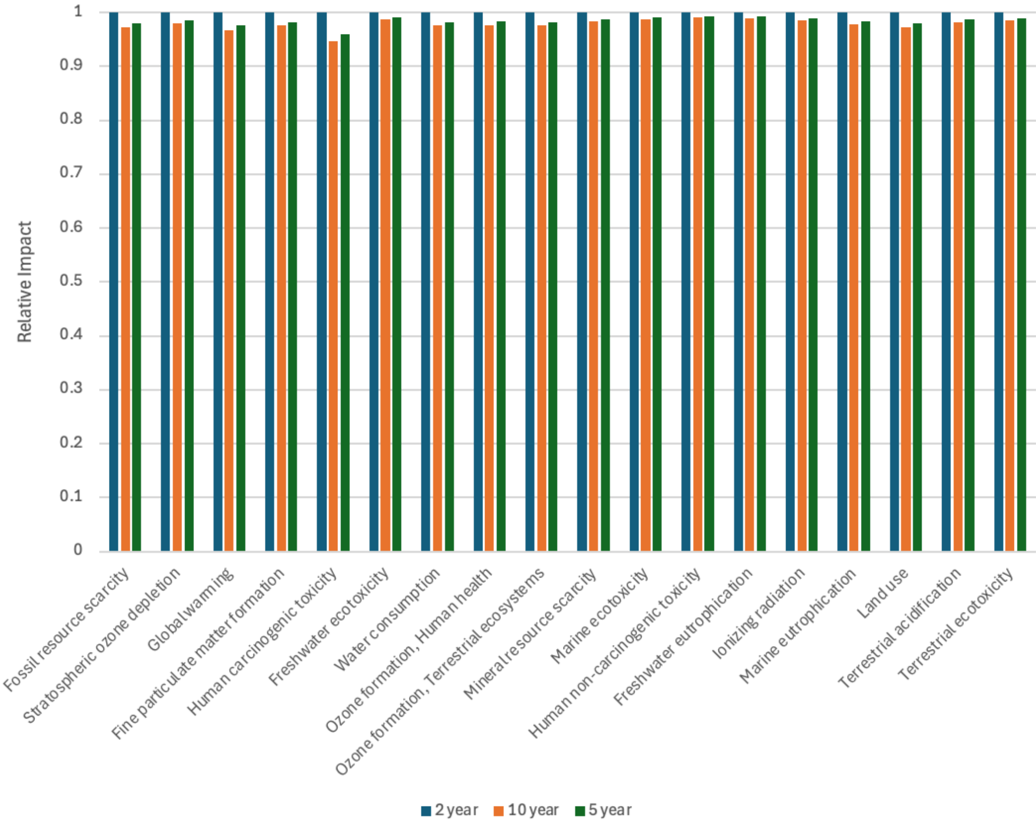

Figure D: Sensitivity analysis on printer lifespan from BASE_MODEL_1. Results display relative total model output using different printer lifetimes based on (Faludi et al., 2015)) over all ReCiPe 2016 impact categories. Based on this SA, it is concluded that lifespan is not a sensitive variable. Especially as two years is not realistic, and the difference between five and ten years is less than 1%, except for a single IC.

Sensitivity analysis 4: use scenario

This SA investigates the effect of different printer use scenarios. Faludi et al. (2015) advices in its recommendations to include different printer use scenarios, as well as printer idling scenarios to more fully capture the lifecycle of a 3D printer. However, the printer used in their study is an early generation, industrial FDM printer with a warmup time of over 40 minutes and a heated three dimensional space. In comparison, in this study a much simpler desktop printer with a heat up time of minutes and just a two dimensional heated bed. Therefore, idling and heat up time are not included in this study as they are neglectable. Several scenarios are selected. Office hours (1500 h/y), half office hours (750 h/y) and full time 24/7 printing (8760 h/y. This variable is also not considered sensitive, as the differences in total output vary only slightly (Figure E). Especially considering the major jump in the number of hours per year.

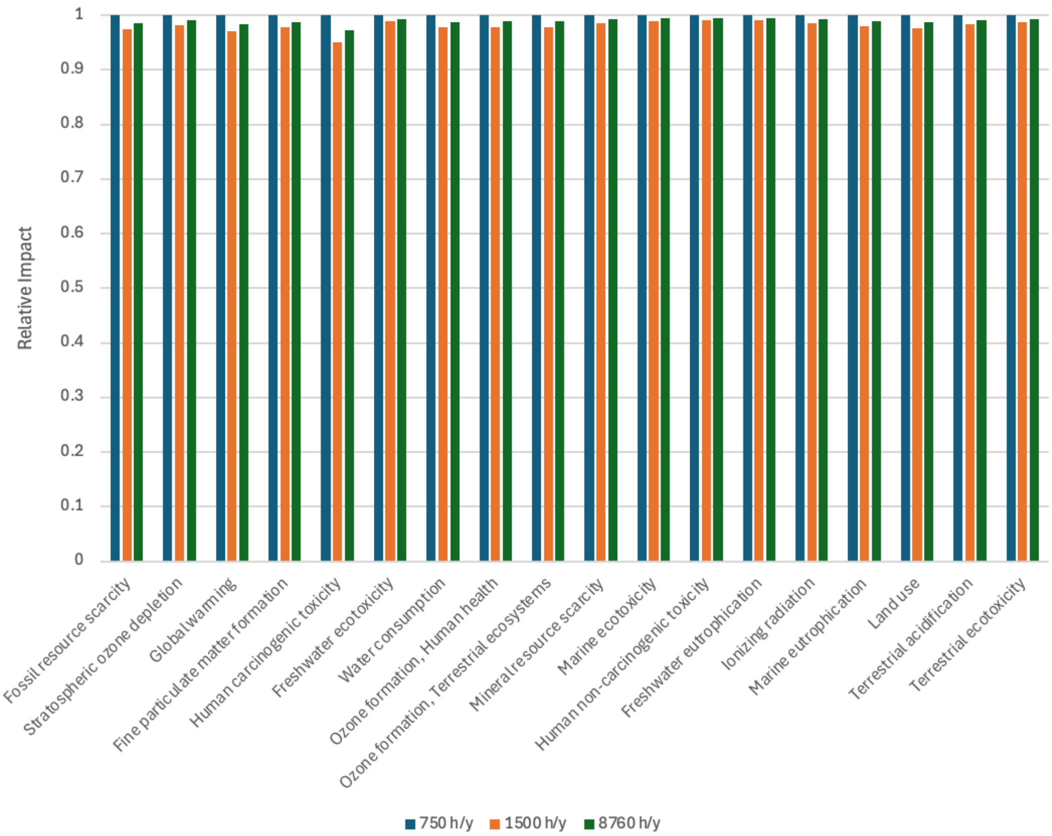

Figure E: Sensitivity analysis on use scenarios from BASE_MODEL_1. Results display relative total model output using different printer use scenarios based on (Faludi et al., 2015) over all ReCiPe 2016 impact categories. Based on this sensitivity analysis concludes that this variable is not sensitive.

D: Variable selection

This appendix further elaborates on the selection of variables as described in the main report in order to answer RQ1. Table C assesses what variables are present in a selection of studies from (Sandez et al., 2024). It concludes that lifespan (extension) and multiple responses to product failure are present in all studies.

Expected and extended product lifetime

Modeling expected lifespan and its extension due to repair varies significantly across literature. A simplified overview of modeling approaches from selected studies is presented in Figure F. Given the absence of a standardized method for defining or modeling expected lifespan and lifespan extension in the literature, this study uses assumptions for these definitions. The “expected life” span for a CM is set at six years, based on the work of (Bovea et al., 2020; Hicks & Halvorsen, 2019). A product failure is assumed to occur after those six years. After this product failure, a repair extends the lifespan a maximum of another six years, referred to as the "extended lifetime". Despite the generally reduced mechanical performance of AM parts (Lay et al., 2019), this study assumes that the production method does not affect product lifespan for reasons of simplification. Furthermore, it assumes only a single repair is carried out during the products lifetime.

Table C: variables present in selected studies from (Sandez et al., 2024).

	Lifespan (extension)*	Multiple responses to product failure**	Consumer behavior	Energy efficiency	Failure types	Other variables
(Pérez-Belis et al., 2017)	X	X	X	x		
(Bovea et al., 2020)	X	X			x	
(Kokare et al., 2023)	X	X	X			Disposal
(Pamminger et al., 2021)	X	X			x	Repair success rates
(Cordella et al., 2021)	X	X				Improved product design
(Bobba et al., 2016)	x	x	x	x		

* Life span (extension) includes some variable of life span before and/or after a failure management occurred.
** Different R-strategies, and/or multiple scenarios of these strategies.

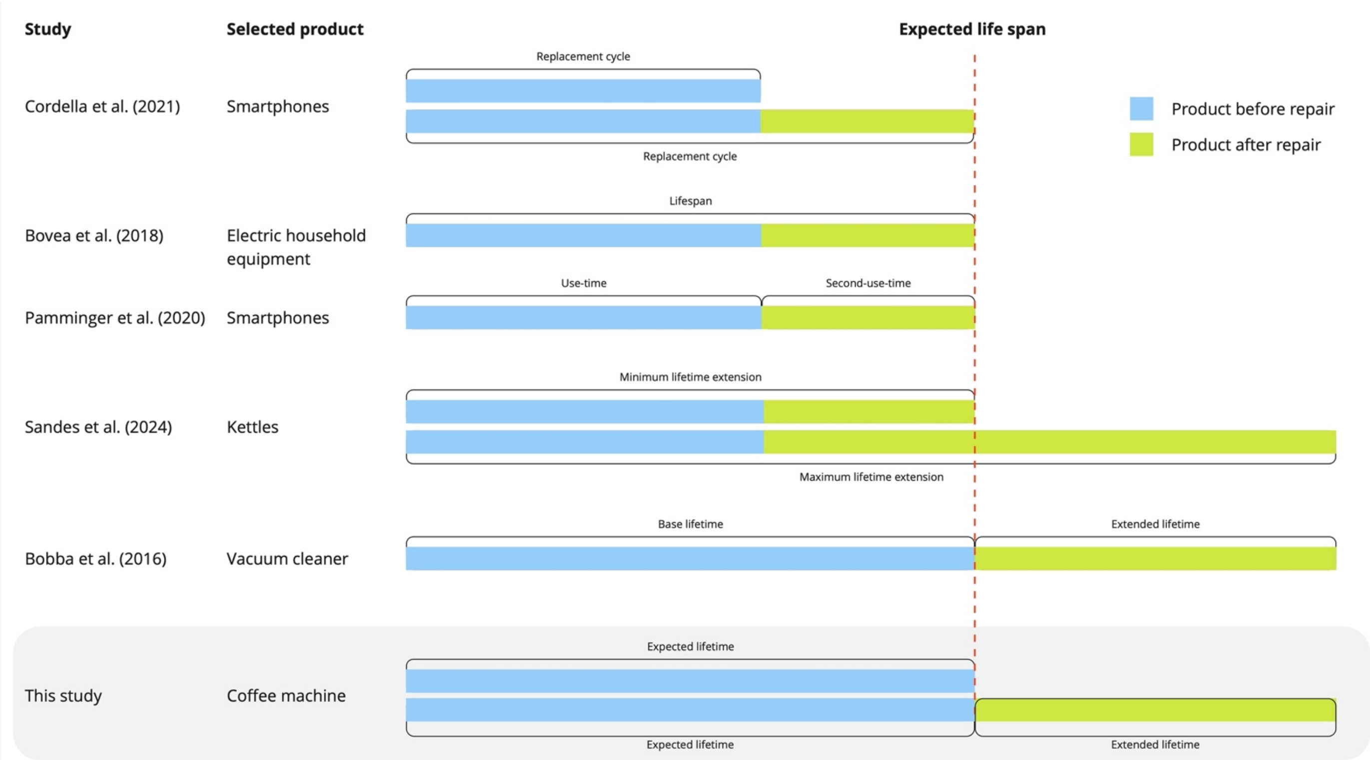

Figure F: overview of lifespan modeling across selected repair LCA studies, including their respective named variables.

Part weight

The selected part weights are derived from real-world part weights obtained through the disassembly of the Philips Senseo CM. Using the assessment criteria outlined in the "3D printing for repair guide" (Arriola et al., 2022), parts were evaluated for their feasibility for AM. Of the total of 74 parts, only eight were deemed feasible for production using AM. These range from 11 to 177 grams. This range is indicative as the variable is dynamic in the final model. In this study, an identical part weight is assumed between an AM and IM RPs that fulfils the same function.

E: Printer build speed for AM-RtPFs

Kokare et al., (2023) compiled data on printer build speed (i.e. 'deposition rate') for FDM print processes through their literature review. However, data is significantly spread, as the study assesses a great variety of FDM printers. Furthermore, an inconsistency in units persists. Therefore, primary data is gathered through the slicing of a selection of 3D models. In total 13 digital parts are used. The models are randomly obtained from the public Onshape Library (Onshape, n.d.), whereafter they are sliced using Ultimakers Cura 5.7 slicer. Slicer settings are described in Table D. From thereon, the (theoretical) print time and part weight are obtained and collected in Table E. The parts are not specifically designed to be optimized for 3D printing as described in the 3D printing for design guide by (Arriola et al., 2022). Printer build speeds average out at a deposition rate of 7.87 gram per hour. This number is in line with findings (Kokare et al., 2023).

Table D: slicer software and relevant settings. Default settings are used unless mentioned here.

Slicing software	Ultimaker Cura 5.7
Selected printer	Ultimaker S5
Material	Generic PLA
Nozzle	0.4 mm
Print settings	Default (0.15mm layer height, 20% infill)
Support	Support added
Part positioning	Optimized for 3d print (based on expert review)

Table E: printer build speed data collected through slicing of 13 randomly selected digital models from the public Onshape Library.

Part name	Author	Print Weight (g)	Print time (hrs.)	Gram / hr.
Iron	Onshape	785	70.13	11.19
Casting	Onshape Training	409	50.92	8.03
1400-PF-1	mirshko	287	37.37	7.68
Linear Part Pattern	Noa	123	10.12	12.16
Spray Hose	Onshape	122	17.07	7.15
step drum frame	Mujip Salam	84	11.32	7.42
Back_Casing	Enoch Park	38	3.50	10.86
Handle_001	tyson dabney	32	5.05	6.34
3DBK Maker Frames	3D Brooklyn	31	5.65	5.49
UMS5_Pannier Replacement Hook	PLTW Engineering	18	2.45	7.35
228-2500-215_60 Tooth Gear	Elliot Mork	12	1.82	6.61
Base 31-2.8	FastwayJim	4	0.63	6.32
Meteorite Cap Carriage	James Jameson	2	0.35	5.71
Average		**150**	**16.64**	**7.87**

F: Transport scenario for IM-RtPFs

The following transport scenario is developed for the CM, as well as its IM RP. The following scenario start at the factory gate [PL] and ends at the consumer [NL]. The starting point as well as the end country is known. From thereon, the rest of this scenario is filled in with a possible, but fictive route and means of transport. The scenario assumes that the product / RP is ordered through an online third party reseller. The reseller is chosen on Google Search engine ranking for online RP availability for the Philips Senseo HD6569/00 CM.

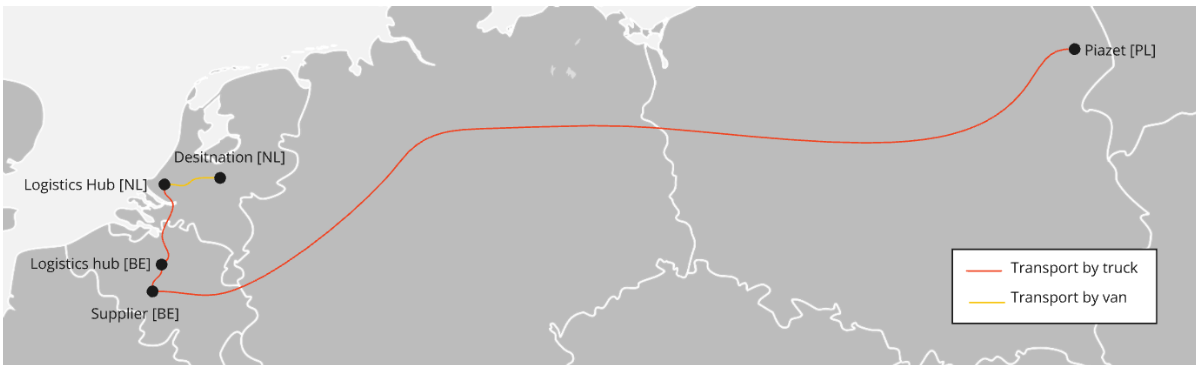

Figure G: partly fictive transport scenario as used for the transport of coffee machine and injection molded replacement part based on Table F, map. Lines follow roughly fastest driving route as provided by Google Maps on Nov 26, 2024.

Table F: partly fictive transport scenario as used for the transport of coffee machine and injection molded replacement part, data.

From	To	Distance (km)	Mode of transport	To address	Comment	Source
Factory	Storage	-	-	Generała Władysława Andersa 44, 15-113 Białystok, Poland	Senseo is produced in Poland by Biazet. Assumed on-side storage	(Biazet, n.d.; Manufacturing Journal, n.d.)
Storage	Directrepair.eu	1554	Truck, EURO 5 > 32 tons	Rue du Parc Industriel 32, 7822 Ghislenghien, Belgium	Assumed reseller: Directrepair .eu	Based on Google Maps, as of Nov 26, 2024
Directrepair.eu	DHL Regional hub BE	40	Truck, EURO 5 > 32 tons	Ternat Essenestraat 26, 1740 Ternat, Belgium	DHL as carrier is assumed Shipping through DHLs closest hubs.	Based on Google Maps, as of Nov 26, 2024. (DHL, n.d.-a)
DHL Regional hub BE	DHL Regional hub NL	215	Truck, EURO 5 16-32 tons	Laan van Waalhaven 10, 2497 GJ Den Haag, Netherlands		Based on Google Maps, as of Nov 26, 2024 (DHL, n.d.-b)
DHL Regional hub NL	Consumer	60	transport, freight, light commercial vehicle	Utrecht Centraal, 3511 CA Utrecht	Selected vehicle closest proxy for delivery van in Ecoinvent. Final location assumed: Utrecht central station.	Based on Google Maps, as of Nov 26, 2024
Total distance (km)		1594	Truck, EURO 5 > 32 tons			
		215	Truck, EURO 5 16-32 tons			
		61	light commercial vehicle			

G: Warehousing impact for IM-RtPFs

The impact of warehousing and handling is estimated based on the following assumptions described in Table G. One 'unit' is a single RP send through the logistics system. For simplification purposes, one size parcel is assumed to represent all RPs. Building hall use per unit is calculated using Equation 6 and electricity consumption per unit is calculated using Equation 7.

Table G: variables for warehousing impact.

Variable	Variable abb.	value	Unit	Source / comment
Assumed warehousing style		Wide-Aisle Racking	-	As described by (Fichtinger et al., 2015)
Pallet density of WA	Pallet_density	1.2	pallets / m2	Table 2 (Fichtinger et al., 2015)
Inventory holding time	Inv_time	6	months	Assumption
Assumed box size		120x80x100	mm	Assumption
Assumed unit weight		95	gram	Average package weight according to Appendix D: Variable selection
Number of units per pallet	n.o._units	720	units	Pallet volume calculator by (Premier Tech, n.d.)
Floor space hall	Floor_space	1500	m2	Steel building construction hall by (Ecoinvent, n.d.)
Life span hall	Life_span	50	years	Steel building construction hall by (Ecoinvent, n.d.)
Lighting	Lighting_EC	36	kWh/m2/year	table 3 of (Fichtinger et al., 2015)
Heating, ventilation and air conditioning (HVAC)	HVAC_EC	300	kWh/m2/year	table 3 of (Fichtinger et al., 2015)
Mobile Handling Equipment (HMME)	HMME_EC	0.26	kWh/pallet	Based on average travel distance as described in (Fichtinger et al., 2015)

Equation 6: accounted share of 'building use' per unit

$$1/pallet\_density/life\_span/n.o.\_units/\frac{12}{inv\_time} \approx 1.157441\text{E}-5m^2$$

Equation 7: electricity consumption per unit

$$\frac{(lighting\_EC + HVAC\_EC) \times pallet\text{\_density} \times \frac{inv\_time}{12} + HMME\_EC}{N.o.\_units} \approx 0.280361111\ kWh\ /\ unit$$

The weight of the cardboard shipping box in which the RP is send is assumed to be 80 grams. This assumption is based on the defined dimensions in Table G and the specifications of a selected shipping box by (PostNL, n.d.). Furthermore, craft paper with a weight of 25% that of the shipping box is assumed to be used as filler material per unit.

H: Bill of Materials Philips Senseo HD6569/00 BOM coffee machine

This chapter presents the mass-based BOM for the Philips Senseo HD6569/00 CM. Unless mentioned otherwise, data is obtained through physical disassembly and weighing (n=1, resolution of 1 gram) of the CM. Figure H shows the result of the CM disassembly. All parts are sorted per material and category before weighting. Two distinct subassemblies are found during disassembly: 'boiler' and 'vibration pump'. Other parts are categorized as 'general'. Not all parts and materials are implemented in the UPT (supplementary_data_A), but some are clustered for model simplification as is indicated in the notes / assumption section. Selected processes are made into foreground processes in order to capture geographical accuracy in accordance with defined LCA scope: raw materials are sourced globally, whereas production process occur within Europe. Due to model simplification, custom foreground processes are only made for major material groups. Transport is taken from Table E.

Table H: BOM of Philips Senseo HD6569/00 coffee machine. Obtained through physical disassembly and weighing (n=1, resolution of 0.0001 kg)

Category	Description	Material	Mass (grams)	Manufacturing process	Notes / assumption	(Ecoinvent) process
Polymer parts						
General	Casing, water tank, internal covers.	Poly Propylene	658	Injection molding	71% of all rigidi polymers are known to be Poly Propylene. For simplification, All rigid polymers are modelled under this material.	poly propylene parts, for CM production, RER*
General	Group head assembly, filter assembly.	Poly Propylene + 30% glass filling	229			
General	Drip tray, buttons, linkage etc.	Acrylonitrile Butadiene Styrene	141			
General	Decorative plating	Poly Carbonate	56			
General	Nozzle housing	Polyoxymethylene	35			
Boiler	Boiler casing	Poly Amide	69			
General	Caps, tube connectors, valves, casings etc.	Misc. rigid polymers	21	Injection molding	No visible material mark. Some metal left in vibration pump casing. Assumed PP, see comment above.	
Vibration pump			26			
Boiler			2			
General	Seals, tubes, dampers, cable strain relief.	Misc. elastomeric polymers	48	Injection molding, extrusion	No visible material mark. Therefore assumed 'synthetic rubber'	market for synthetic rubber, GLO
Metal parts						
General	Heat sink	Aluminum	30	Stamping, misc.		market for aluminum, wrought alloy, GLO
General	Drip tray, filter holder, nozzle cap	Stainless steel	134	Stamping, misc.	Some polymers still included in pad holder	metal parts, for CM production, RER*

General	Screws, springs, brackets, heat spiral, boiler cap etc.	Misc. metal parts	14	Wire drawing, thread rolling, pipe extrusion, misc.	Small parts unidentifiable. Assume "hot formed steel"	
Vibration pump			55			
Boiler			58			
Boiler	Spool, connectors, wires	Copper	8	Wire drawing, misc.		market for copper, cathode, GLO
Vibration pump			59			
Electronics						
General	Printed Circuit Boards	Misc.	29	Misc.		market for printed wiring board, surface mounted, unspecified, Pb free, GLO
General	Power cable	Copper, Poly Vinyl Chloride (assumed)	95	Wire drawing, injection molding. misc.	For simplification combined into single process.	market for cable, unspecified, GLO
General	Wires		18			
Other						
Boiler	Heat conductor in spool	Magnesium Oxide	47	Calcination		market for magnesium oxide, GLO
Packaging	Product box	Corrugated cardboard	650	Paper manufacturing, corrugation, die-cutting, printing, misc.	Packaging mass derived from (Philips, n.d.)	market for corrugated board box, GLO
Total Weight			2482	grams		

* these processes are custom foreground processes in order to capture geographical accuracy in accordance with defined LCA scope: raw materials are sourced globally, whereas production process occur within Europe. Due to model simplification, custom foreground processes are only made for major material groups.

Figure H: Results of the disassembly of Philips Senseo HD6569/00, all parts sorted by material and category.

I: Bill of Materials Ultimaker 5s+ 3D printer

For BASE_MODEL_1, a SA was conducted on the bill of materials (BOM) of the 3D printer used (see Appendix C: BASE_MODEL_1, Figure B). The analysis concluded that the specific composition of the 3D printer is not a critical factor. Given the similarity between BASE_MODEL_1 and BASE_MODEL_2—both in system architecture (as seen in the flow charts) and input variables (as indicated by UPTs)—this conclusion is assumed to hold for BASE_MODEL_2 as well. To optimize time and resources, the BOM of the Ultimaker 5S+ from BASE_MODEL_1 is therefore also applied in the final LCA model, BASE_MODEL_2.

Table I: assumed BOM for the Ultimaker 5S+ 3D printer. Assumption validated through sensitivity analysis (Figure B) produced from Appendix C: BASE_MODEL_1.

Category	Description	Material	Mass (grams)	Manufacturing process	Notes / assumption	Ecoinvent process
Steel parts						
Steel parts	Frame, linear rails, shafts, pulleys, fasteners, misc.	Steel, unalloyed	5500	Hot rolling, extrusion, thread cutting, misc.		market for steel, unalloyed, GLO
Polymer parts						
Polymer parts	Panels, print head housing, belt (guides), misc.	Poly Carbonate	10325	Injection molding, extruding.	Large mass due to panels assumed to be PC.	market for polycarbonate, GLO
Electronics						
Cable	Power cable, wires, cable tree	Copper, Poly Vinyl Chloride (assumed)	1000	Wired drawing, injection molding. misc..		market for cable, unspecified, GLO
Motor assembly	Motor assembly	Steel, magnets, copper wire.	800	Misc.	"Electric motor, for electric scooter" selected as best motor alternative in Ecoinvent.	market for electric motor, for electric scooter
PCB	Printed Circuit Board	Misc.	125	Misc.		market for printed wiring board, surface mounted, unspecified, Pb free
Fan	Fan	Poly Propylene, steel, copper wire	350	Misc.		market for fan, for power supply unit, desktop computer, GLO
Display	LCD display unmounted	ABS, Aluminum, PCB	250	Misc.	Display module comparable to earlier generations of mobile LCD displays as that of Ecoinvent.	Market for liquid crystal display, mobile device, unmounted ,GLO
Other						
Glass	Print bed, window	Flat glass	2250	Glass floating, misc.		market for flat glass, uncoated, GLO
Total Weight			20600	grams		

J: Flow charts

This appendix contains all flow charts. Figure I to Figure K display flow charts for BASE_MODEL_2, the model used for the main report. Figure L is the flow chart for BASE_MODEL_3. This model is used for MCS as described in appendix K: Model uncertainty. All flow charts are also attached to this report as separate files.

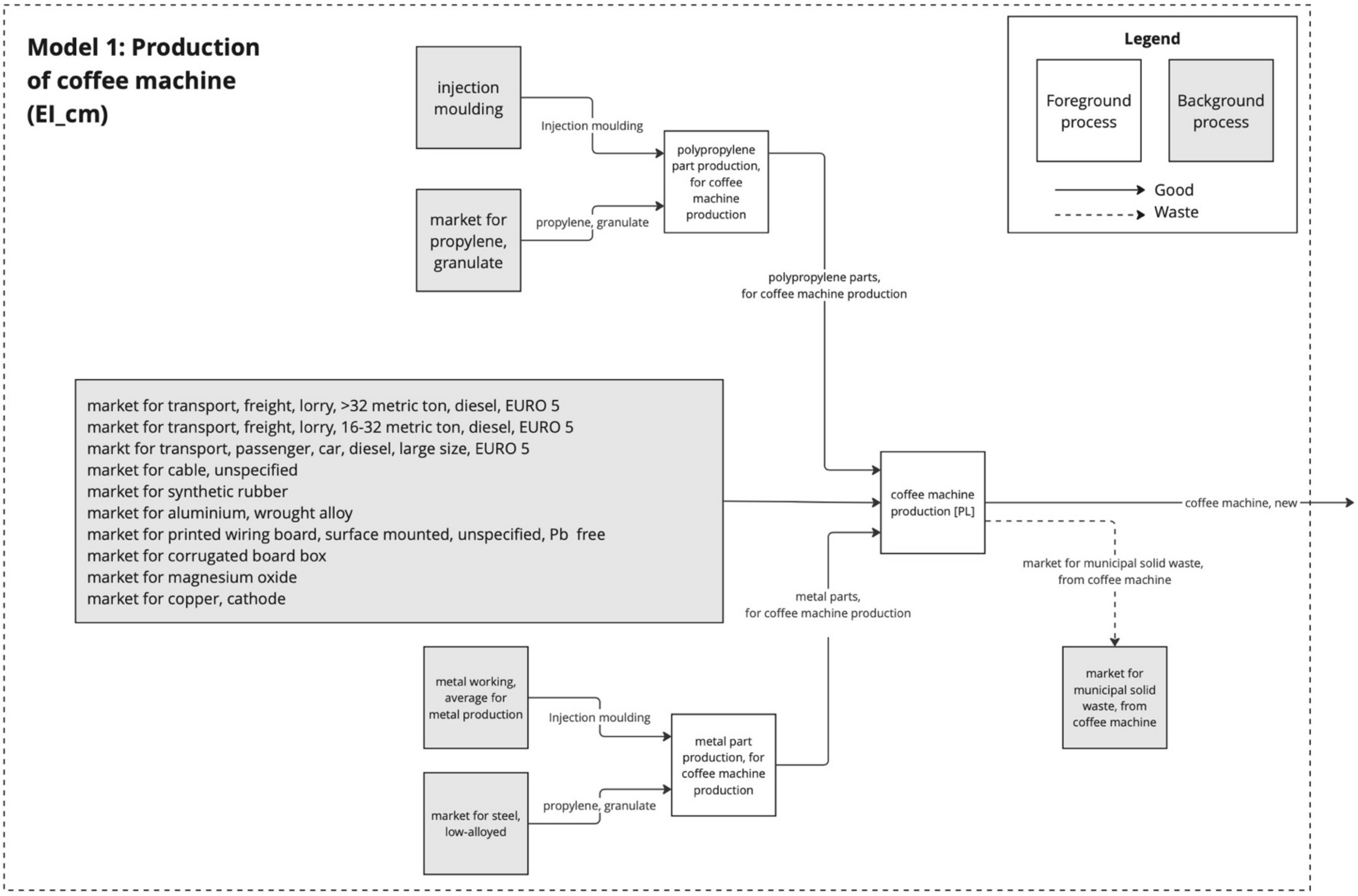

Figure I: Flow chart of sub-system 'Production of coffee machine' in BASE_MODEL_2.

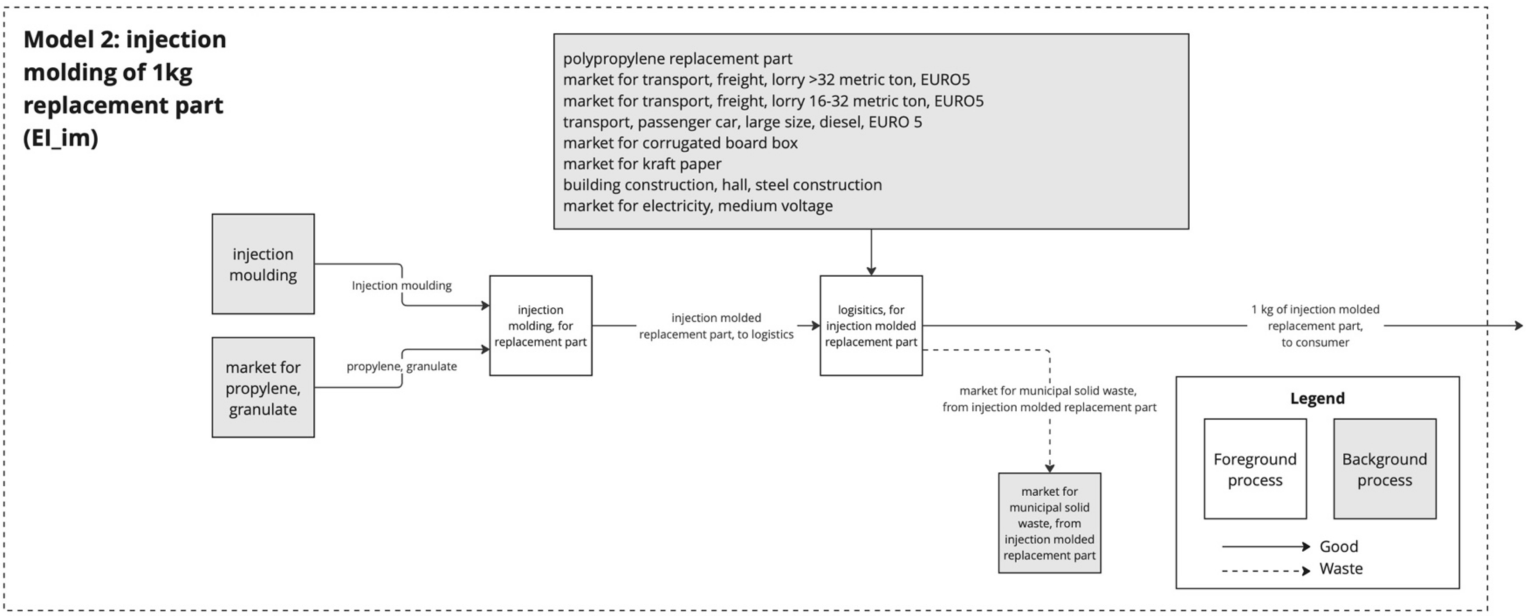

Figure J: Flow chart of sub-system 'Injection molding of 1kg replacement part' in BASE_MODEL_2.

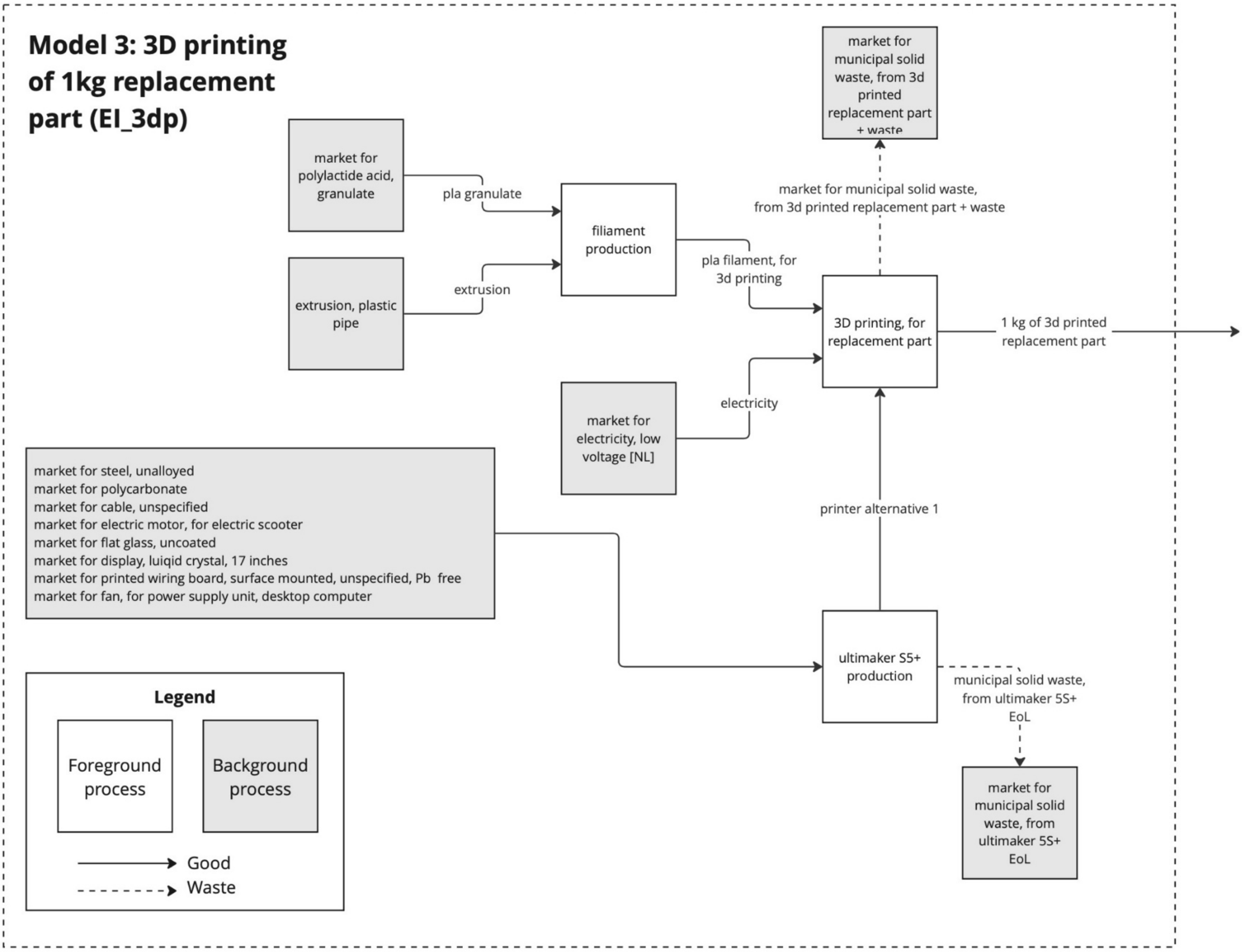

Figure K: Flow chart of sub-system '3D printing of 1kg of replacement part in BASE_MODEL_2.

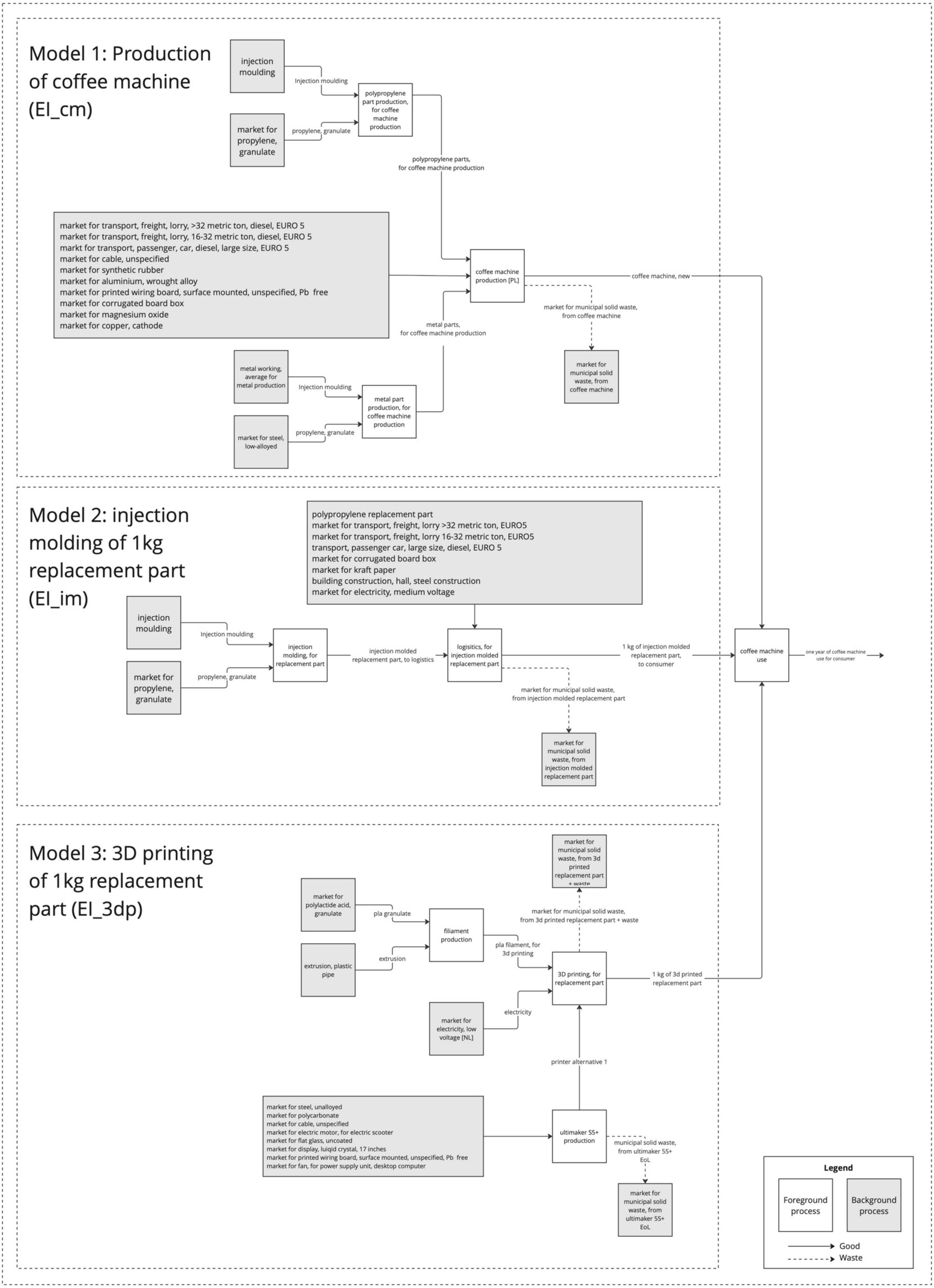

Figure 3: Flow chart of the product system, including **Error! Reference source not found.** to

K: Model uncertainty

This appendix further discusses the erroneous Ecoinvent uncertainty data, MCS implementation as well as the number of MCS runs.

Erroneous uncertainty data.

MCS is typically performed on the entire LCA model, including both foreground and background processes (Bruijn et al., 2006). However, erroneous background data in the Ecoinvent database leads to incorrect results. For instance, the mean results between a model calculation and MCS for the same product system differed by a factor of 2. Additionally, the standard deviation for several impact categories was up to 8 times larger than the mean. Examples of these faulty results are shown in the MCS Histogram (Figure M). This issue has been reported by OpenLCA users (2022), OpenLCA (Cilleruelo, 2023), and Ecoinvent itself (Ecoinvent, 2023). While Ecoinvent attempted to fix this error in version 3.9.1, it persists in version 3.10, affecting this study's results and others (OpenLCA, 2022). As a result, MCS was performed only on the foreground processes, where data quality is manually assessed and can be guaranteed.

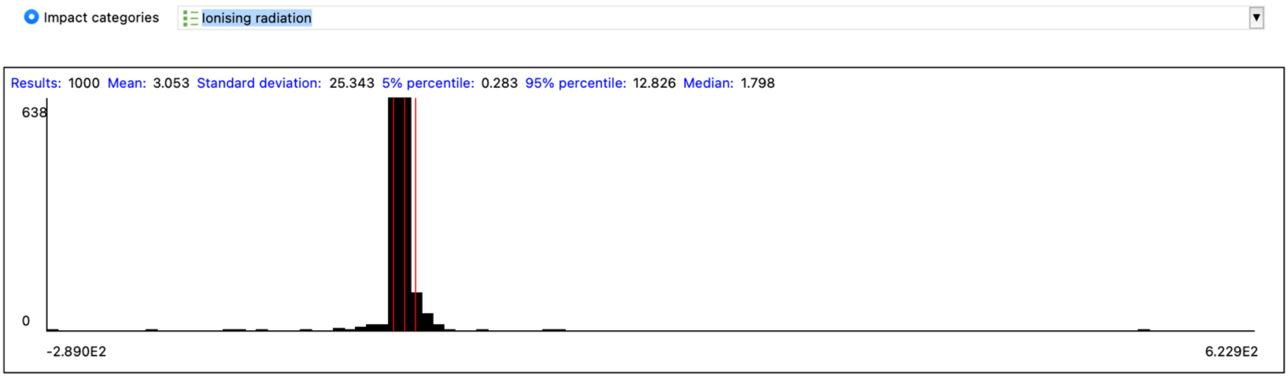

Figure M: screenshot from OpenLCA presenting a faulted Monte Carlo Simulation histogram. The Mean is twice as big as the mean found through system calculation, and the standard deviation is a factor eight larger compared to the mean.

Monte Carlo Simulation implementation

Due to time and resource limitations, it is unfeasible to perform a MCS for every possible combination of input variables for the SET (Figure 9). Therefore, one uncertainty value is calculated per RtPF for every IC. In order to perform this calculation, the following variables are fixed: L_exp = 6 year, L_ext = 4 year, M_part = 40 gr whereas RtPF changes per MCS. A separate LCA model is created in OpenLCA (BASE_MODEL_3 (ecoinvent 9.1).zolca), combining the three sub-models from Figures 18 to 20 into a single model, with the final result shown in Figure L. The combined model uses three parameters (‘f_cm_y’, ‘m_im_y’, and ‘m_3dp_y’) to define the relationships between the sub-models and generate the final output per ‘year of coffee machine use.’ These parameters act as ‘manual inputs’, replacing the equations used for BASE_MODEL_2. Table J defines and calculates the values for these parameters based on the performed MCSs. BASE_MODEL_2 and BASE_MODEL_3 validate each other, as they produce the same environmental impacts for identical variable inputs (part mass, lifetime extension, and RtPF).

Number of runs

In LCA literature, it is common to run between 1000 and 10.000 MCSs, without providing specifics about this number (Igos et al., 2019). A high number of MCS runs might lead to very precise, but inaccurate results, incorrectly suggesting a high quality of research. Therefore, Heijungs (2020) argues to restrict the number of monte carlo runs to be not greater than the sample size of the provided data, as the imprecision also makes up for potential inaccurate results. When uncertainty is estimated through a procedural uncertainty estimation, such as the pedigree matrix, it is often unclear what the data sample size was. This is the case with the ecoinvent database used in this study. Therefore, Heijungs advice against the use of MCS in combination with the procedural uncertainty estimation Peligree matrix. Despite this discrepancy, no further insights are be found in literature that could shed a light on a ‘correct’ number of runs, nor does Heijungs (2020) provide a solution to this problem. Therefore, a number of 2000 runs is assumed for this study as it is within the range commonly used for MCSs in LCA.

Table J: variables used in Monte Carlo Simulations in order to obtain uncertainty data for inputs ‘f_cm_y’, ‘m_im_y’ & ‘m_3dp_y’ of BASE_MODEL_3, model variables are fixed at L_exp = 6 year, L_ext = 4 year, M_part = 40 gr.

		fraction of 'coffee machine' accounted for per year of CM use		Mass of IM RP accounted for per year of CM use.		mass of AM RP accounted for per year of CM use.	
System name	RtPF	Formula	f_cm_y	Formula	m_im_y	Formula	m_3dp_y
MCS_1_Replace	Replace	1/L_exp	0.166666667	-	0	-	0
MCS_2_IMRP	IMRP	1/(L_exp+L_ext)	0.1	M_part/ (L_exp+L_ext)	0.004	-	0
MCS_3_IMRP-2	IMRP-2	1/(L_exp+L_ext)	0.1	(M_part*2)/ (L_exp+L_ext)	0.008	-	0
MCS_4_IMRP-5	IMRP-5	1/(L_exp+L_ext)	0.1	(M_part*5)/ (L_exp+L_ext)	0.02	-	0
MCS_5_IMRP-10	IMRP-10	1/(L_exp+L_ext)	0.1	(M_part*10)/ (L_exp+L_ext)	0.04	-	0
MCS_6_AMRP	AMRP	1/(L_exp+L_ext)	0.1	-	0	M_part/ (L_exp+L_ext)	0.004
MCS_7_AMRP-2	AMRP-2	1/(L_exp+L_ext)	0.1	-	0	(M_part*2)/ (L_exp+L_ext)	0.008
MCS_8_AMRP-4	AMRP-4	1/(L_exp+L_ext)	0.1	-	0	(M_part*4)/ (L_exp+L_ext)	0.016
MCS_9_AMRP-6	AMRP-6	1/(L_exp+L_ext)	0.1	-	0	(M_part*6)/ (L_exp+L_ext)	0.024
MCS_10_AMRP-8	AMRP-8	1/(L_exp+L_ext)	0.1	-	0	(M_part*8)/ (L_exp+L_ext)	0.032
MCS_11_AMRP-10	AMRP-10	1/(L_exp+L_ext)	0.1	-	0	(M_part*8)/ (L_exp+L_ext)	0.040

K: Parts of coffee machine feasible for AM

All parts of the Philips Senseo HD6569/00 have been assessed for their reproducibility using AM. As standard, the assessment criteria depicted in GUIDE are used. Strictly yielding these criteria results in only eight parts that are feasible for AM, as displayed in Table K. Main reasons for the inability for AM are, simplified and in order of occurrence: lacking material specifications, complex part design, food contact, smooth surface.

Table K: coffee machine parts feasible for AM, based on assessment criteria of (Arriola et al., 2022).

Part name	Weight (grams)
Lid housing	177
Top cover plate	78
Coffee nozzle cover plate	41
Drip tray container	36
Locking lever top plate	21
Lid housing	15
Locking mechanism linkage	14
Closing nob	11