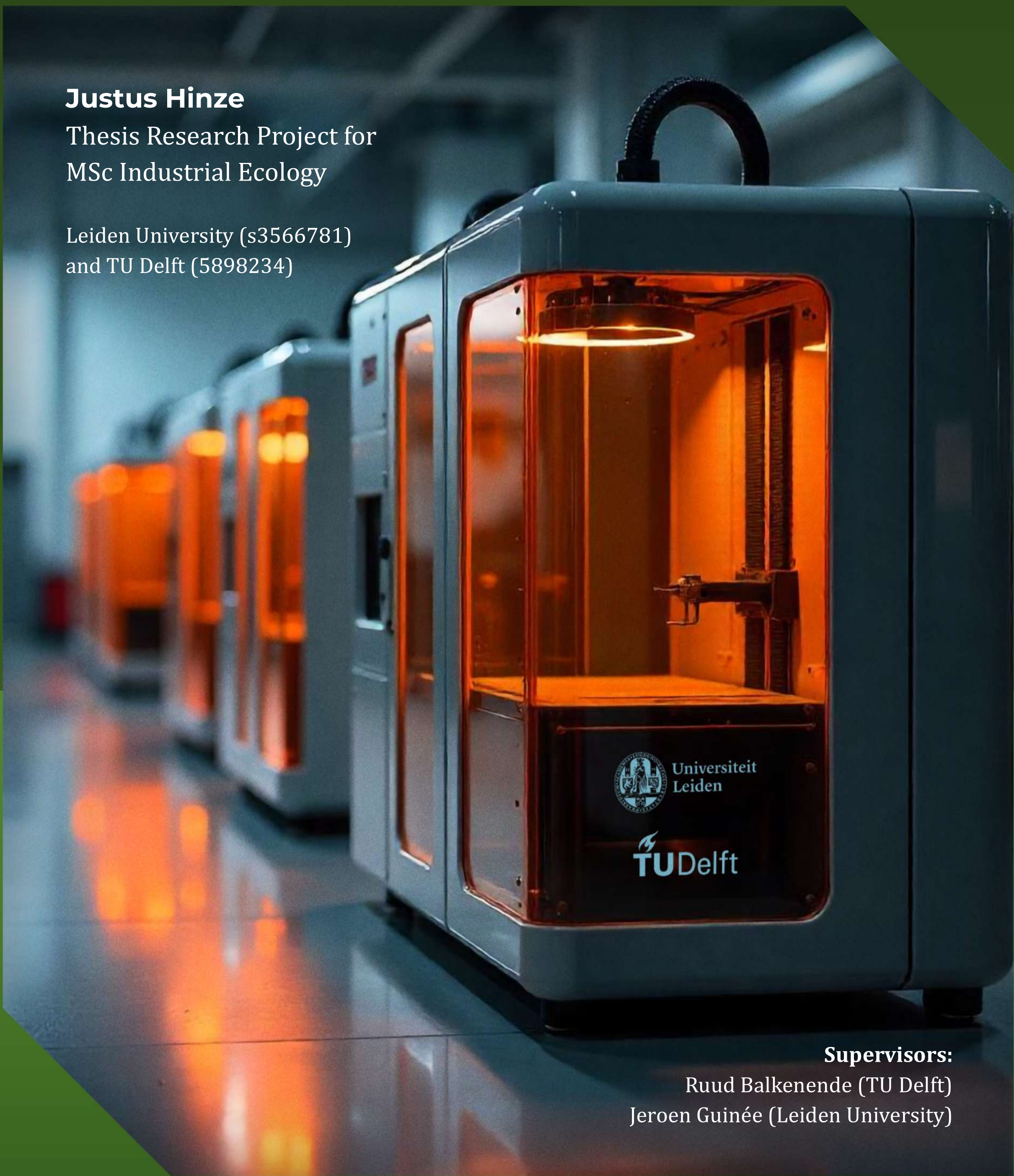
Thesis Research Project – 2025

On-Demand or Stockpiled?

A Prospective LCA of Additive Manufacturing vs. Traditional Spare Part Strategies



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Abstract

The recently launched Ecodesign for Sustainable Products Directive from the European Commission requires that spare parts for consumer products like washing machines be available for up to 10 years. This requirement poses challenges to current spare part strategies, as it increases the need for storage and demands more sustainable practices in spare part production and management. While additive manufacturing (AM), particularly stereolithography (SLA) printing, is recognised for its potential to minimise stockkeeping, waste, and transportation, most life cycle assessments (LCAs) have primarily focused on the printing process. Consequently, overall impacts related to logistics and storage, when compared to traditional injection moulding (IM), remain underexplored.

A critical knowledge gap remains in understanding how technological and material improvements, production scale, storage duration, and recycling practices influence the overall environmental performance of these strategies. In this study, a prospective LCA was conducted on a plastic washing machine spare part to evaluate these parameters. The assessment indicated that under current conditions, the SLA printed spare part has approximately twice the environmental impact of the IM and its 10-year stored alternative. However, future advancements in energy efficiency, resin formulations, printer lifetime extension, and other improvements could significantly reduce the environmental impacts of SLA and potentially make it competitive with IM. It was also found that while storage and transport requirements do increase the impacts of IM, the material impacts play a more crucial role. The assessment also revealed a crossover point for impacts at production volumes of around 250–350 parts, below which SLA becomes preferable.

These findings provide critical insights into sustainable long-term spare part provisioning and offer guidance for manufacturers and policymakers on enhancing the environmental sustainability of spare part provision. They also emphasise key development areas for researchers and AM technology developers to advance the sustainability of AM. Future research should focus on enhancing resin inventory data, examining recycling impacts, accurately assessing per-part energy consumption, and comparing more recent AM technologies with traditional manufacturing to determine the conditions under which performance crossovers occur.

Key Words: Right-to-repair, Spare Part Availability, Additive Manufacturing, Injection Moulding, Stereolithography, Prospective Life Cycle Assessment, 3D Printing in Spare Part Supply, Sustainability in Manufacturing, Environmental Impact Assessment

Table of Contents

Glossary

ABS = Acrylonitrile-butadiene-styrene

AM = Additive manufacturing

EF = Environmental Footprint

EoL = End of Life

FU = Functional Unit

IM = Injection Moulding

LCA = Life Cycle Assessment

LCI = Life Cycle Inventory

LCIA = Life Cycle Impact Assessment

pLCA = Prospective Life Cycle Assessment

SLA = Stereolithography

WM = Washing Machine

Declaration

I acknowledge using Grammarly and Chat GPT to refine the writing of this thesis. These tools were utilised to enhance the clarity, grammar, and coherence of the writing while ensuring that the ideas, analysis of results, and conclusions are entirely my own.

1. Introduction

1.1. Problem Context

1.1.1. Extended Product Lifetime and Repair

Over the past century, human production and consumption patterns have significantly impacted our environment by depleting finite resources and causing harmful emissions, calling for a societal and economic shift toward more sustainable practices (Clift & Druckman, 2016). Although recent policy efforts have primarily aimed at decoupling economic growth from environmental impacts, Parrique et al. (2019) found minimal empirical evidence for this approach. They stress that in order to achieve sustainability within planetary boundaries, it is crucial to move beyond simply pursuing efficiency measures and instead adopt a philosophy of sufficiency, which entails reducing levels of production and consumption.

To address these environmental issues, the European Commission (2019) launched the Green Deal, which seeks to minimise greenhouse gas emissions, decouple economic growth from resource consumption, and guarantee a fair transition. Although grounded in the premise of maintaining economic growth, various strategies have been implemented to lower overall resource use. For example, the Circular Economy Action Plan focuses on industries with significant resource consumption and prospects for circularity – such as electronics and plastics – by encouraging sustainable product design and consumption while retaining resources within the EU (European Commission, 2020). Additionally, legislative efforts like the Ecodesign Directive (2009) and its extension into the Ecodesign for Sustainable Products Directive (2024) highlight the significance of product longevity, reusability, recyclability, and the provision of spare parts to lower consumption and resource use (European Commission, 2009, 2024). For example, new regulations mandate that crucial spare parts for household appliances must be available for at least 10 years to keep products in use for longer (European Commission, 2019).

Minimising overall consumption is crucial, as the industrial manufacturing sector accounts for roughly 15% of global energy usage and 35-40% of material consumption (Hegab et al., 2023). Additionally, prolonging the lifespan of consumer goods is essential; their early disposal results in around 261 million tons of CO_2-equivalent emissions, consumes 30 million tonnes of resources, and generates 35 million tonnes of waste, translating to an annual consumer loss of about €12 billion in the EU (European Commission, 2020). Of particular concern are electrical and electronic devices, which contain valuable materials like metals, highlighting the necessity to transition from conventional waste management to approaches that focus on extending product life, such as enhancing maintenance, reliability, repairability, and upgradability (Bracquené et al., 2021). Although promoting product longevity through repair is pivotal, the success of these efforts largely depends on the availability and management of spare parts (Bracquené et al., 2018; van Hollander, 2018).

1.1.2. Spare Part Management

Access to spare parts is crucial for maintaining product functionality and minimising downtime, which ensures operational efficiency and prolongs product life, preventing early disposal due to a single-part failure (Van der Auweraer et al., 2017; Zhang et al., 2021). Effective management of spare part inventories, ensuring timely availability, is vital as it prevents expensive production delays or halts (Zhang et al., 2021). While companies try to reduce shortages by keeping safety stock buffers, this strategy can be costly, with maintenance, repair, and operations inventories making up to 40% of procurement budgets (Van der Auweraer et al., 2017). According to Zhang et al. (2021), unlike for capital goods, spare part demand for durable consumer goods is highly unpredictable due to fast product development and shorter life cycles, requiring tailored, cost-efficient inventory strategies to address these variations. They also noted that original equipment manufacturers often finalise production prior to a product coming to market, complicating spare part demand forecasting during the warranty period. Furthermore, rapid product developments raise retooling costs for suppliers and lead to shortages of older models. Given the difficulties of managing long-term inventories, where many parts can remain unused, resulting in extra costs and unnecessary environmental impact, there is a pressing need for alternative production methods to reduce the need for stockkeeping.

1.1.3. Additive Manufacturing

This is where additive manufacturing (AM), a set of production methods that researchers have explored over the last two decades, presents a compelling option (Cardeal et al., 2022; Gao et al., 2015; González-Varona et al., 2020; Pérès & Noyes, 2006; van Oudheusden et al., 2024; Zhang et al., 2021). With AM, a product is built layer by layer based on a 3D model, which reduces raw material usage by utilising only what is necessary and eliminating the need for tooling (Hegab et al., 2023; Huang et al., 2013; Kokare et al., 2023). Its main benefits include lower material waste compared to traditional subtractive processes, the capability to create complex geometries, options for mass customisation, shorter production lead times, and decentralised manufacturing reducing transport needs (Hegab et al., 2023; Huang et al., 2013; Kokare et al., 2023). Since tooling such as moulds for injection moulding (IM) is not necessary, AM allows for a "digital warehouse" concept where instead of keeping physical parts, only digital 3D printing files are stored (Cardeal et al., 2022; González-Varona et al., 2020; van Oudheusden et al., 2024). This supports innovative business models, permitting parts to be printed on-demand wherever there is an appropriate AM machine, leading to localised manufacturing with decreased inventory costs, logistical needs, and supply chain delays (Cardeal et al., 2022; González-Varona et al., 2020; van Oudheusden et al., 2024). AM particularly excels in producing high-value, low-volume components as it circumvents the limitations of traditional economies of scale, allowing for rapid design adjustments and mass customisation (Tofail et al., 2018). Although the AM process may consume more energy, benefits arising from new design possibilities, such as lightweighting, which can reduce energy use during the operational phase of the product – provided that significant functional improvements, such as reduced fuel consumption, are achieved (Kellens et al., 2017)

Nonetheless, challenges remain in the widespread implementation of AM. While cost and time savings drive the adoption of AM for repairs in some instances, its speed and unit cost overall remain less competitive compared to traditional mass production methods, which limits its application for high-volume spare parts (Gao et al., 2015; Hegab et al., 2023). Moreover, the certification of AM processes and parts presents hurdles, as manufacturers need to guarantee consistent quality to mitigate liability concerns related to 3D-printed components (Hegab et al., 2023). They also emphasise the difficulties in adopting innovative AM-based business models and setting up distributed maintenance systems, while the actual advantages of these product-service models have yet to be proven (Hegab et al., 2023). There are also significant redesign efforts needed to maintain functionality, as most parts are initially designed for, e.g. IM rather than AM, being particularly challenging for parts with complex geometries and material-specific properties (van Oudheusden et al., 2024).

Despite these operational challenges, researchers have also raised concerns regarding the actual sustainability of AM compared to traditional manufacturing. For instance, AM processes are known to consume significantly more energy than traditional manufacturing (Kellens et al., 2017; Shi & Faludi, 2020). While most studies focus on energy consumption, comprehensive data on resource use, direct and indirect process emissions, and the impacts of feedstock production are insufficient (Kellens et al., 2017). Although AM can provide material efficiency advantages over traditional manufacturing, it may also shift or even exacerbate environmental issues throughout various life cycle phases, given that factors such as part geometry, machine utilisation, production volume, and material type can influence whether AM is more or less sustainable than traditional manufacturing (Cerdas et al., 2017; Kokare et al., 2023). The overall sustainability of AM in comparison to conventional manufacturing is highly context dependent. In some cases, AM can be more sustainable, but it may lead to higher environmental impacts when energy consumption is particularly high or when high-impact raw materials are used (Kokare et al., 2023).

1.2. Research Gap

Despite extensive research into AM, its overall sustainability impact, and potential for spare part supply remain underexplored. Kellens et al. (2017) and Peng et al. (2018) found that current studies predominantly focus on energy usage during specific AM processes, which has left significant gaps regarding resource usage, process emissions, and the environmental impacts of feedstock production. Moreover, Hegab et al. (2023) and (Kokare et al., 2023) highlight the necessity of a comprehensive life cycle sustainability assessment of AM; existing life cycle assessments (LCAs) on AM usually do not go beyond the production stage to encompass material production, post-processing, transportation, and end-of-life (EoL) management. This gap is especially evident in spare parts, where comparative sustainability analyses between AM and traditional manufacturing processes are lacking (Zhang et al., 2021). The two processes differ significantly concerning material extraction, equipment impacts, production energy, logistics (such as long-term storage and overproduction for traditional manufacturing), and disposal. Furthermore, scholars stress the importance of predictive environmental impact assessments for AM that investigate new materials and technologies (Kokare et al., 2023), as well as the conditions under which AM can become a feasible alternative to traditional manufacturing (Cardeal et al., 2022).

1.2.1. Method

Current research lacks a comprehensive sustainability evaluation comparing AM and traditional manufacturing throughout their life cycles while also considering their future development potential, as AM is still a less mature technology than IM. LCA is a method for quantifying all relevant environmental impacts of a product system from extraction to disposal, aiming to identify potential improvements in environmental performance, and is defined in the ISO 14040 series (Guinée & Heijungs, 2024). Prospective Life Cycle Assessment (pLCA) extends this method by modelling technology scenarios for emerging technologies such as AM as they scale (Arvidsson et al., 2018). Mendoza Beltran et al. (2020) enhanced this by integrating scenario-based approaches, such as integrated assessment models, to provide a more robust long-term sustainability assessment, making it a suitable method for evaluating the future potential of AM in spare part provision.

1.2.2. Case Study

In order to make this research more concrete, it will explore the environmental potential of AM through a case study on washing machine (WM) components. They are a particularly relevant case study due to their significant contribution to waste electrical and electronic equipment, accounting for 55% of large household appliance waste in Europe (Bracquené et al., 2021). Despite having an average lifespan of 12.5 years, WMs are frequently discarded due to technical failures, even though many of these failures – such as issues with electronics, pumps, and bearings – are repairable (Bracquené et al., 2018, 2021). However, Tecchio et al. (2016) found that repairs are often hindered by high perceived costs, limited spare part availability, and design constraints that make disassembly difficult. Spare part availability is also particularly challenging, as many components such as motors or pumps are brand or machine-specific despite fulfilling similar functions, limiting the interchangeability and requiring large inventory stocks (Dangal et al., 2022). In this context, AM presents a promising solution for producing product-specific plastic parts without necessitating extensive inventories (van Oudheusden et al., 2024).

1.2.3. Novelty

By exploring the environmental implications of AM for spare part production, this study addresses key sustainability challenges in prolonging the lifespan of consumer products and reducing electronic waste. This study is novel as it is the first to integrate pLCA into evaluating long-term spare part provision strategies of AM and IM, thereby capturing future technological, economic, and policy developments that previous studies overlooked. In addition, this research not only compares the impacts of the technologies themselves but also incorporates supply chain and EoL considerations, offering a more comprehensive sustainability assessment of the two technologies in the context of long-term spare part storage than previous studies.

1.3. Research Objectives and Questions

Based on identified gaps in the literature, this study aims to evaluate the environmental effects of providing spare parts over the long term. To accomplish this, the main research question is:

> *What long-term spare part provision strategy (on-demand SLA printing versus injection moulding and storage) provides the most sustainable solution for spare plastic housing components of washing machines?*

And the following sub-questions have been formulated:

1. *What are the most frequently failing plastic components in washing machines, and what specific performance requirements determine their compatibility with SLA manufacturing?*
2. *What alternative scenarios can be defined for the long-term provision of the selected plastic housing spare part via injection moulding and SLA printing, what is the most appropriate functional unit for comparing these, and which key parameters are critical in shaping their future developments?*
3. *What are the life cycle environmental impacts and organisational implications of on-demand SLA printing compared to injection moulding under current and future conditions for the two scenarios?*

1.4. Thesis Outline

This thesis is structured as follows: Chapter 3 examines the existing landscape of WM spare parts and assesses the suitability of a chosen reference part, which serves as a case study for the pLCA. Chapter 4 details the scenarios developed for spare part provision and describes the steps undertaken in the pLCA process. Chapter 5 presents the findings, which are further analysed in Chapter 6, where the various strategies and trade-offs for spare part provision are discussed in terms of sustainability.

2. Research Approach

This study's overall research flow and deployed methods to answer each sub-research question are outlined in Figure 1 and consisted of three phases. The first phase focused on identifying the commonly failing components of WMs and evaluated their suitability for SLA printing (Chapter 3). In the second phase scenarios were established and the environmental impacts of the two spare part provision strategies were evaluated through pLCA (Chapters 4 and 5). Lastly, the different spare part strategies, future developments and trade-offs were discussed (Chapter 6).

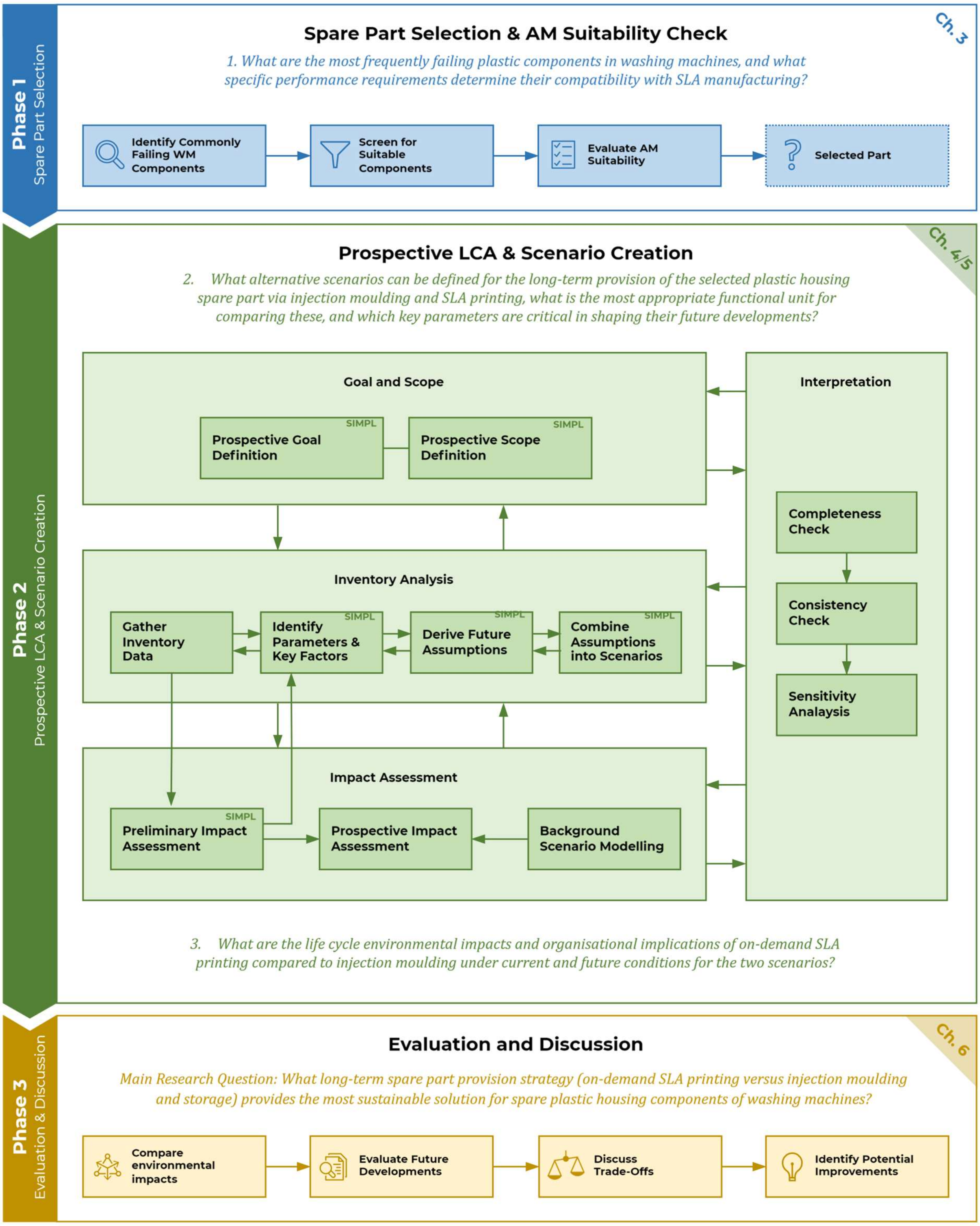

Figure 1: Research flow diagram, covering the three phases.

2.1. Phase 1: Spare Part Selection and AM Suitability Check

The initial phase, detailed in Chapter 3, focuses on identifying an appropriate component for analysis. This involves researching frequently failing components, assessing their relevance to the case study on the plastic housing component, and evaluating their compatibility with SLA printing according to AM design criteria established by van Oudheusden et al. (2024). The objective of this phase is to address the first sub-research question:

1. *What are the most frequently failing plastic components in washing machines, and what specific performance requirements determine their compatibility with SLA manufacturing?*

2.1.1. Component Selection Process

The first step in this analysis is to research commonly failing WM components by reviewing both academic and non-academic sources on WM repairs. To ensure that the study focuses on components that would benefit most from the flexibility of AM, the resulting list of components is then screened according to the study's goals, prioritising non-standardised plastic components with a high repair frequency and unique design features. Van Oudheusden et al. (2024) found these to be particularly suitable for AM, compared to standardised components like bolts and pipes, which are more effectively manufactured through traditional manufacturing. Although it is technically possible to manufacture components from materials other than plastic (e.g. metal) using AM, these parts, along with those containing complex electronics such as screens or sensors, have been excluded from this study's scope. From the resulting list of potentially suitable WM components, one is chosen for further analysis.

2.1.2. Evaluation of AM Suitability

The second step assesses if the chosen part fits the selected AM technology. This involves using a list of design requirements established by van Oudheusden et al. (2024), which associates structural and material properties with design criteria. These criteria are then used to compare the capabilities of three different AM technologies (selective laser sintering, stereolithography, and fused deposition modelling) against IM (see Table 1).

Table 1: Design requirements for plastic IM spare parts based on van Oudheusden et al. (2024)

Group	Design Requirement
Geometry	Shape, detail, accuracy and tolerances
Configuration	Water-/air tightness, multi-material, surface finish, transparency
Mechanical	Strength, flexibility (bend), elasticity (stretch/ compress), impact resistance, abrasion resistance, fatigue resistance, creep resistance
Thermal	Heat resistance, cold resistance
Chemical	Water resistance, UV resistance, chemical resistance, food safety

When evaluating the part against these criteria, we derive a table with the component's requirements and its technology capability ratings (green, yellow, red) for each technology – in this case, IM and SLA. A green rating indicates full compatibility, yellow highlights potential challenges requiring further design optimization, and red signals significant limitations where the technology might not meet the required specifications. Components receiving predominantly yellow or red ratings are flagged as candidates for redesign or for developing alternative designs to ensure functional equivalence between production methods. SLA has been chosen as the preferred technology for this study, as van Oudheusden et al. (2024) generally found its capabilities to be comparable to those of IM. However, they emphasise that a part is defined through the interplay of its requirements, which influence one another. While a part might be suitable for SLA (indicated by all green), there may, for instance, be challenges in combining design requirements such as transparency and flexibility with SLA. Although the technology can technically achieve both requirements individually, in this case, the transparent resins are known to be more brittle and thus not suitable for achieving the necessary level of transparency, compromising flexibility. This evaluation is presented more illustratively since the actual redesign of the selected component lies outside the scope of this study. Nevertheless, it will indicate whether the part requires a redesign to be compatible with both IM and AM or if two distinct parts should be created that are functionally equivalent, where the original part is produced using IM, and the replacement part is made with AM.

2.2. Phase 2: Prospective LCA and Scenario Creation

After confirming the technical feasibility for AM of the chosen spare part, the subsequent step is to develop the provisioning scenarios for the spare parts and assess their environmental impacts. This second phase, outlined in Chapter 4, focuses on developing the spare part scenarios using the SIMPL method established by Langkau et al. (2023). It also evaluates the environmental impacts of the two strategies and scenarios over time, adhering to the general LCA steps described earlier. Additionally, this phase incorporates the modelling of background system changes through the Premise approach from Sacchi et al. (2022), utilising the Activity Browser software developed by Steubing et al. (2020). The aim of this phase is to address the following two sub-research questions:

2. *What alternative scenarios can be defined for the long-term provision of the selected plastic housing spare part via injection moulding and SLA printing, what is the most appropriate functional unit for comparing these, and which key parameters are critical in shaping their future developments?*

3. *What are the life cycle environmental impacts and organisational implications of on-demand SLA printing compared to injection moulding under current and future conditions for the two scenarios?*

2.2.1. LCA Framework

The principles of LCA have been defined in the ISO 14040 series and follow four iterative phases (Guinée & Heijungs, 2024):

1. **Goal and Scope:** Define the goals of the study, system boundaries, scope, functional unit, and alternatives.
2. **Inventory Analysis (LCI):** Gather and quantify all relevant input and output flows.
3. **Impact Assessment (LCIA):** Quantify the environmental impacts.
4. **Interpretation:** Analyse results and draw conclusions

Each of these steps is iterative, with the outcomes of a subsequent phase enhancing decisions or assumptions made in a previous phase and directing, for instance, where more in-depth data collection is necessary. Nevertheless, despite the iterative nature of this process, only the final version of each phase will be reported to ensure clearer communication.

The **goal and scope** phase is concerned with formulating the question that the study seeks to answer and establishing its context. This involves clarifying its intended application and audience (goal) and defining the system boundaries of what is included in the product system, the selection of impact categories, and the treatment of uncertainty (scope). Outcomes of this phase also include the selected alternatives for comparison (e.g. IM and SLA), as well as the functional unit (FU), which represents the function of the products based on which the alternatives are assessed.

During the **inventory analysis** phase, all necessary inputs and outputs of a product's life cycle stages are collected and quantified. This entails gathering inventory data for all unit processes (the smallest element of the product system for which data is collected, e.g. IM machine production) from both academic and non-academic literature (e.g. material or energy inputs for SLA printing), performing calculations to scale it to the outflow of the unit process, and ultimately creating a table that encompasses all relevant inputs and outputs of each alternative's unit processes in relation to the FU.

The **impact assessment** focuses on evaluating the magnitude and significance of the environmental impacts of the assessed product systems. This involves characterisation, wherein the LCI results are converted to common units and aggregated for each impact category (e.g., greenhouse gas emissions such as CO2, CH4, and N2O, using characterisation factors to derive the total impact indicator results for climate change). An optional step in this phase is normalisation, where the results are expressed as a share of the total impact in a region, indicating which impact category a product contributes to relatively significantly; however, Guinée & Heijungs (2024) emphasise that the normalisation results are biased due to missing data. An optional step is weighing, where the normalised results are multiplied by a weighting factor that represents a specific value judgement about the importance of one impact category result in relation to another. This process enables the aggregation of results from each impact category into a single impact score for each alternative. While this simplifies the comparison of alternatives, researchers found that the weighting is highly dependent on these normalisation factors and may, therefore, produce biased results (Heijungs et al., 2007; Prado et al., 2020). To evaluate whether normalisation and weighting inflate the aggregate impacts, a normalisation and weighting contribution check was incorporated. The results of this assessment can be found in Appendix Z, File VIII, along with the normalisation and weighting factors used from the EF3.1 family. Detailed discussions of these methodological choices, their limitations, and influence on overall results are provided in Section 6.3.2.

The **interpretation** of the results is where findings from the LCI and LCIA are evaluated regarding the goal and scope of the study by identifying significant issues (e.g., life cycle phases with highest impacts or trade-offs between alternatives), evaluating the completeness, sensitivity, and consistency of the model, and deriving conclusions, limitations, and recommendations.

2.2.2. Integration of SIMPL

While various approaches to scenario development for LCAs have been employed over the past decade, Langkau et al. (2023) introduced a structured stepwise method that enhances the goal, scope, and inventory analysis of the LCA framework with additional steps for future scenario development.

SIMPL Goal and Scope
In the SIMPL framework, the goal and scope phase is extended by **defining the prospective goal, time horizon, scenario types, as well as prospective scope**. The time horizon is typically when the technology reaches maturity and has permeated the market. The temporary boundaries are

set in the future and must remain valid and consistent across all parameters. Scenario type refers to whether it is explorative (i.e. what if) , predictive (i.e. likely), and normative (i.e. desirable). This study follows an explorative approach where the influence of parameters that have been highlighted in the literature on AM as potential improvements on the outcomes is explored while grouping them into more "realistic" and "ambitious" parameter changes. Prospective scope changes may be about that in a later development stage of the technology, the FU or geographical scope may change as its technology readiness level is increasing and diffuses in the market. In this case study, only the reference years in the reference flows will change, as decentralised production is already feasible. Thus, the geographical scopes will not need to be adjusted with maturity of technology.

SIMPL Inventory Analysis

The SIMPL framework integrates three additional steps into the inventory analysis phase to develop scenarios in conjunction with gathering the inventory data. These steps are iterative, with preliminary impact assessments and their interpretations helping to refine the parameters and assumptions, ultimately leading to the final inventory model.

1. Step: **Identify the relevant inventory parameters and key factors**,
2. Step: **Derive future assumptions for the key factors and parameters**,
3. Step: **Combine the assumptions into future scenarios**.

The initial step involves **identifying the key inventory parameters and factors** by creating a preliminary inventory model and performing a sensitivity analysis. The inventory parameters consist of quantified elementary and intermediate flows (e.g., inputs for recycling plastic mixes), while key factors operate at a higher level and affect one or more of these flows (e.g., recycling share policies). Langkau et al. (2023) also recommend organizing the parameters hierarchically (e.g., electricity mix and, subsequently, the shares of various electricity generation technologies). They suggest using a PESTEL checklist (considering political, economic, sociological, technical, environmental, and legal aspects) to clarify and comprehensively identify these parameters. Additionally, creating a causal loop diagram linked to the inventory model can illustrate how inventory parameters influence one another and highlight possible interdependencies. Although this study does not explicitly undertake these last steps, which would more thoroughly explore other influential parameters identified in the literature, such an approach would enhance future research by uncovering additional factors affecting developments AM.

The second step involves **deriving future assumptions for the key factors and parameters** by adopting existing assumptions or establishing new ones, ultimately selecting a set of assumptions based on their distinctiveness. Utilising assumptions from already established scenarios in literature (e.g., concerning projected recycling rates) proves advantageous as it conserves time and resources by leveraging widely accepted or recognised scenarios, thereby facilitating discussions of the results within these contexts. In instances where such existing assumptions are unavailable, it becomes necessary to derive them qualitatively before quantifying them (e.g., the absence of policies related to printer efficiency necessitates projecting these improvements based on current performance and historical development trajectories). Finally, when various assumptions about a parameter exist (such as different levels of energy efficiency or recycling rates), it's beneficial to choose more distinct ones that enable the examination of multiple "what-if" scenarios. For instance, a 30% reduction in energy efficiency over 20 years could be seen as a moderate or realistic assumption, while a 70% reduction may be considered significant or ambitious, and more granular steps may only provide limited additional insight. In this research, there will be three distinct scenarios for each technology. The “base” scenario represents the worst case (i.e. no improvements to the technology are made), the “realistic” scenario reflects plausible improvements, and the best-case or “ambitious” scenario considers what would happen if significant technological advancements are achieved. As there are no concrete development trajectories for SLA printing, the assumptions will primarily be established qualitatively, while the subsequent sensitivity analysis will reveal whether they significantly influence the results.

The final step focuses on **combining the assumptions into future scenarios** while ensuring they remain consistent and distinct. The consistency check aims to exclude inconsistent combinations among the foreground parameters (e.g. energy efficiency and recycling share), as well as with the background parameters. Although the consistency check may allow many possible scenarios, the distinctness-based selection process effectively narrows them down. This aids in enhancing clarity and reduces research efforts by choosing adequately different scenarios. The outcomes derived from these more distinct scenarios also enable inferential conclusions regarding the scenarios that fall in between. Although explicit consistency checks and detailed causal loop diagrams were not conducted in this study due to scope limitations, this research still captures the overall trends and major parameter interdependencies as indicated by the literature (e.g., print speed and energy efficiency trade-off). Furthermore, consistency is implicitly assured since all scenarios are classified as "positive” or improvement scenarios where only the order of magnitude of the combinations in a scenario may be debated. The “realistic” scenarios are based on current trajectories, assuming moderate technological improvements, while the “ambitious” scenarios diverge further from these trajectories.

The outcome of these steps is to create a table that includes all key parameters, projections for their changes over time for the various scenarios, and the implementation of these into a so-called “scenario difference file," as explained in the next section.

2.2.3. Background Scenario Modelling

Incorporating background scenario modelling is crucial, as pLCA faces significant epistemological uncertainty. Consequently, Mendoza Beltran et al. (2020) proposed a novel approach whereby the background database (in this study, Ecoinvent) is systematically transformed based on integrated assessment model scenarios (e.g., various future electricity mixes), such as the IMAGE model. They concluded that integrating these changes renders the assessment more robust. Sacchi et al. (2022) expanded upon this approach by automating these database transformations for particularly energy-intensive activities using the “Premise” tool. The industries that are currently covered are transport, power-, steel-, cement-, and fuel production. In this study, these background transformations will be conducted in the “Activity Browser”, a graphical user interface for the Python-based LCA framework Brightway that facilitates the combination of background scenarios through the ScenarioLink plugin alongside foreground scenarios via scenario difference files (SDF; Steubing et al., 2020).

2.3. Phase 3: Evaluation & Discussion

In the final phase of this study, the pLCA outcomes are critically evaluated both in terms of the environmental implications of the strategies, evaluating future developments, discussing trade-offs and identifying the biggest improvement potentials, to address the main research question:

- *What long-term spare part provision strategy (on-demand SLA printing versus injection moulding and storage) provides the most sustainable solution for spare plastic housing components of washing machines?*

While the first part is already covered in the interpretation phase of the pLCA, it extends beyond the direct environmental impact comparison by reflecting on the overall research process. Specifically, it considers whether the integration of the prospective steps, using the SIMPL framework and background scenario modelling, led to significant shifts in the conclusions, improved the robustness of the analysis, and ultimately informed strategic decision-making while also identifying potential improvements.

3. WM Spare Part Selection and AM Suitability

This chapter describes the process of identifying frequently failing WM components and evaluating their compatibility with SLA printing, ultimately selecting one reference component that will serve as the basis for the pLCA. It is organised as follows: first, common WM component failures and repair challenges are examined (Section 3.1.1); then, the components are screened to match the criteria of this study (Section 3.1.2). Next, the design requirements of each component are compared against the capabilities of SLA printing (Section 3.2.1), and finally, the research question is answered (Section 3.2.2).

3.1. Component Selection Process

3.1.1. Identify Commonly Failing WM Components

Most Common WM Component Failures

According to Bracquené et al. (2018), the average lifespan of a washing machine (WM) in the literature is 12.5 years, with an average failure rate of 6.8% over 10 years of use. As illustrated in Figure 2, the most frequent parts to fail include the electronics, carbon brushes, shock absorbers, drain pump, door seals, motor, water hose, and bearings (Bracquené et al., 2021). However, the most repaired components are the doors and carbon brushes, while in nearly 50% of cases, repairs involving electronics, shock absorbers, and bearings were not carried out (Tecchio et al., 2016). According to Tecchio et al. (2016), approximately 69% of device failures can be successfully repaired. The primary reasons for not pursuing repairs are as follows: in 78% of cases, repairs were technically feasible but perceived as too costly by consumers; in 15% of cases, repairs were considered technically impractical due to issues such as unavailability of parts or challenging disassembly designs; and in 7% of cases, repairs were viewed as too expensive to pursue (based on a subset of data, considering only cases with single failure modes; Tecchio et al., 2016). Replacement of a component occurred in 58% of cases, while 27% required no spare parts for repairs (Tecchio et al., 2016).

WM Repair Process and Spare Part Challenges

Dangal et al. (2022) evaluated the average disassembly time required to access specific WM and dryer parts across ten different models. They discovered that removing drum bearings and the tub assembly took the longest time. This was followed by hoses, shock absorbers, pumps, electronics, and door seals. In contrast, the shortest disassembly times were observed for the door, heater, and door lock. In terms of facilitating repair, Dangal et al. (2022) found opportunities in the standardisation of WM components. It was concluded that the pumps are often brand- or product-specific, with no clear reason, despite essentially performing the same functions. However, the varying connecting interfaces rendered most pumps incompatible with other models. Similar to the pumps, brushless motors were found to be product/brand specific despite performing the same functions. Also, the drum pedal attachment interface to the drum has the potential for standardisation, while another issue was the presence of non-removable bearings, which make the entire tub assembly economically unrepairable. They concluded that it would be preferable to have standardised, easily removable interfaces that allow for repairs.

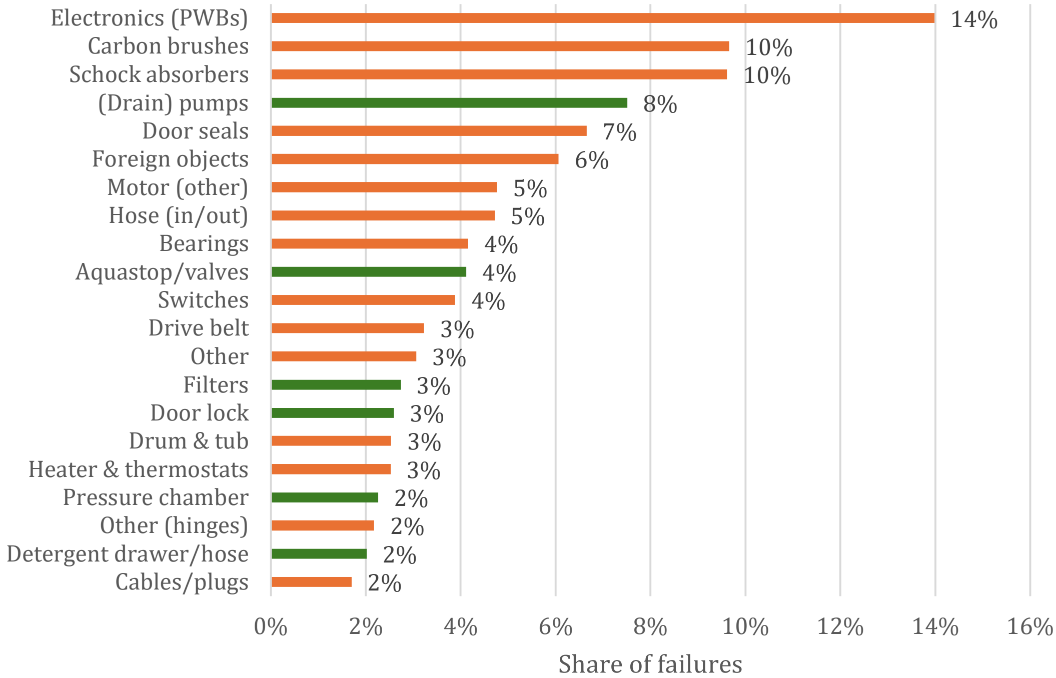

Figure 2: Frequency of WM component failure (adapted from Bracquené et al., 2021; data from Tecchio et al., 2016). Failures highlighted in green were considered to be potentially repairable using AM spare parts.

Opportunities for Improved Repairability through AM

The findings by Tecchio et al. (2016) indicate that while a significant percentage of WM component failures can be repaired, in 78% of cases, the perceived costs and complexities associated with repairs often deter consumers. In 15% of cases, the repairs were considered impractical due to poor design for repairability (e.g. parts break during the process) or the unavailability of spare parts, providing potential case for on-demand AM. The potential for improved repairability through the standardisation of components presents an opportunity to enhance the sustainability of WMs in the market. For this case study, AM of spare parts can potentially streamline the repair process by enabling the production of components that are otherwise difficult to find as they are not standardised.

3.1.2. Screen for Suitable Plastic Components

The focus of spare part selection is on small to medium-sized, non-standardised, product-specific plastic components that present significant repair challenges, aligning with the scope of this study and what Iftekar et al. (2023) identified as particularly suitable cases for AM. SLA is the selected printing technology since van Oudheusden et al. (2024) found its capabilities comparable to IM. Other materials and technologies are considered outside the scope of this study.

Of all the WM components (for the full list, see Appendix A, Table 1), those listed in Table 2 have been identified as potentially suitable for this case. These parts mainly consist of plastic, with a few featuring basic electronics like sensors for the door lock or a small motor for the drain pump. While the drum tub (the plastic shell around the metal drum) is theoretically possible to manufacture using SLA printing, its large size and mechanical stress render it unsuitable for most SLA printers. Among the list, the drain pump stands out as a suitable candidate for further analysis due to its relatively high failure share (fourth position among top failures in Figure 2) and its typical brand or model specificity, as noted by Dangal et al. (2022). Although it includes a motor and wiring, these are assumed to be standardised and purchased externally, while the spare part housing design can be adjusted to fit the specific WM model. Since AM permits customisation of the interfaces to pipes and filters, it is theoretically possible to even reproduce pumps for old WMs that are out of production, provided that data on the interface dimensions and requirements remains available. Consequently, it is the ideal candidate for further evaluation using the design criteria established by van Oudheusden et al. (2024).

Table 2: Selected potentially AM suitable WM components.

Group	Component	Comment	Failure Share
Drum	Drum Paddles	Low complexity, high mechanical stress	n/a
Door	Handle	Low complexity, moderate mechanical stress	n/a
	Lock	Fine details, involves sensors, moderate mechanical stress	3%
Water Management	Drain Pump	Multi components, contains motor, water tightness, smooth surfaces, moderate mechanical stress	8%
	Filters	Low complexity, water tightness	3%
	Aquastop	Accurate fit, water tightness, standardised	4%
	Pressure Chamber	Moderate complexity, water tightness	2%
	Detergent Drawer	Mostly plastic, low force, smooth surfaces	2%

3.2. Evaluate AM Suitability

3.2.1. Assessing Design Requirements

Reference Part and Disassembly

To assess the actual suitability for AM and determine whether a redesign is necessary, a reference pump has been ordered and disassembled to obtain information on the original production processes, AM suitability, and life cycle inventory (LCI) data. The specific model is designed for Hisense/Gorenje machines with the model number K1911126 and is shown in Figure 3.

Figure 3: Selected washing machine pump for Hisense Gorenje machines with the model number K1911126. Later used as reference for weights of components in the pLCA. Image retrieved from fixpart.nl (FixPart, 2024)

Figure 4 illustrates the disassembly of the pump, highlighting its four primary sub-components: the motor block with the impeller, motor coils and cables, filter, and main pump chassis. Although components like the motor block and the coils include materials beyond plastic, the assessment of AM suitability will focus solely on the plastic housing parts. This choice was made to keep the assessment results more representative for other plastic spare parts and since their impacts do not change between the two technologies as they are sourced externally.

Figure 4: Disassembly of the reference pump and its four main components (photograph taken by author).

Design Requirement Evaluation

Table 3 presents only the design requirements from van Oudheusden et al. (2024) that are relevant to the pump, with the most essential being:

- **High Surface Quality:** Essential to prevent buildup of debris.
- **Water Resistance:** To ensure leak prevention and maintain non-hygroscopic properties.
- **High Accuracy & Tolerances:** Necessary to ensure that threaded interfaces seal properly.

Other parameters, such as strength, impact resistance, abrasion, fatigue, and cold resistance, are relevant but considered less critical for the pump's operational demands. Most pump-relevant criteria are rated green, indicating that SLA performs similarly or better than IM for these design requirements. Only strength and impact resistance received a yellow rating, implying potentially minor challenges that may require design optimisation. Although data on abrasion, fatigue, creep, and cold resistance were insufficient, these properties are deemed less critical for the functioning of the pump, and van Oudheusden et al. (2024) found sources suggesting that SLA can meet these requirements e.g. through specific resins. Overall, the evaluation confirmed that SLA can meet the design requirements of the part, confirming that the pump housing is likely feasible to print without substantial redesign efforts. However, future assessments should consider potential trade-offs between the design properties.

Table 3: AM suitability evaluation of WM pump, based on criteria by van Oudheusden et al. (2024)*. Green: full compatibility, yellow: potential challenges requiring design optimisation, red: significant limitations suggesting redesign is needed.*

Group	Design Requirement	Comment	SLA Capability
Geometry	Shape	Ensure proper fluid flow, few cavities	[green]
	Detail	Moderate wall thicknesses	[green]
	Accuracy & tolerances	Accurate fit and threads need to ensure water tightness	[green]
Configuration	Water-/air tightness	Prevent leaks	[green]
	Surface finish	Remove friction and prevent debris build-up	[green]
Mechanical	Strength	Withstand water pressure	[yellow]
	Impact resistance	Handle vibrations	[yellow]
	Abrasion resistance	Endure wear from water and debris	Insufficient data. Claims of high wear resistance for durable resins.
	Fatigue resistance	Withstand repeated cycles	Insufficient data. Claims of good fatigue properties for some materials
	Creep resistance	Maintain shape under stress	Insufficient data. Common resins may creep, but some claim to be more creep-resistant.
Thermal	Heat resistance	Handles hot wash cycles	[green]
	Cold resistance	Prevents cracking in freezing conditions	Insufficient data. Experimental testing, strong resin unaffected by prolonged exposure below 0.
Chemical	Water resistance	Continuous exposure to water, must be non-hygroscopic	[green]
	Chemical resistance	Resists detergents and cleaning agents	[green]

3.2.2. Final Selected Part

To address the first research question, initially, the most commonly failing WM components, such as electronics, carbon brushes, shock absorbers, and drain pumps, were identified (Bracquené et al., 2021; Tecchio et al., 2016). Among the potentially suitable plastic components, the drain pump housing was chosen, as it is one of the most frequently failing plastic components that is often product-specific and lacks standardisation, complicating spare part inventory management (Dangal et al., 2022). Its moderate complexity, small to medium size, along with the requirement for a smooth, watertight finish, match the capabilities of SLA printing (Iftekar et al., 2023).

The original pump housing is presumably made from ABS plastic. Therefore, Accura ABS-like resin was chosen as a suitable substitute, as it offers comparable mechanical properties – including strength, precision, and moisture resistance (3D Systems, 2021). A reference pump from Hisense/Gorenje was dismantled to gather production and LCI data and to assess the specific design requirements based on van Oudheusden et al. (2024). The key requirements include high surface quality, water resistance, accuracy and precise fit. Ultimately, the combination of SLA printing with the ABS-like resin not only satisfies the design specifications of the pump housing but also serves as a representative combination for a wide range of plastic spare parts.

4. Prospective LCA for the WM Spare Part Scenarios

The objective of this chapter is to answer the second and third sub-research questions by developing alternative spare part provision scenarios, establishing a suitable functional unit, and assessing the environmental impacts of the selected two strategies. For this, the steps for scenario development and conducting the LCA as outlined in the method section 2.2 will be followed.

4.1. Goal and Scope Definition

4.1.1. Prospective Goal Definition

This LCA aims to perform a comparative analysis of two spare part provision strategies (IM with storage vs. on-demand SLA 3D printing) for WM pumps under current and future conditions. This study aims to identify environmental hotspots and assess how technological advancements and evolving market conditions affect the environmental sustainability of each strategy. Specifically, the analysis will address potential benefits and trade-offs for both strategies under current (2025) and future timeframes (2030, 2040, and 2050).

This study’s intended audience includes decision-makers in the appliance repair and manufacturing sectors, as well as other LCA practitioners, providing them with valuable insights to guide the strategic design process for the most sustainable long-term spare parts provision approach. This LCA does not aim to make a public comparative assertion, nor does it include external expert review.

4.1.2. Prospective Scope Definition

This assessment takes a cradle-to-grave perspective, covering the environmental impacts of raw material extraction, manufacturing processes, transportation, use phase, and EoL disposal or recycling. It includes time-dependent modelling for 2025, 2030, 2040, and 2050 to capture future technological advancements and shifts in energy systems. Technological coverage and potential improvements in IM and SLA are based on academic literature, expert judgment, and prospective background inventories.

The study follows the ISO14040 and ISO14044 LCA standards. As background database, Ecoinvent 3.10.1 cut-off by classification is used, and the prospective inventory database is generated using Premise (Sacchi et al., 2022; Wernet et al., 2016). Regarding LCA modelling, Activity browser 2.10.2 with the ScenarioLink plugin was used to perform the IMAGE 3.0 scenario transformations (Stehfest et al., 2014; Steubing et al., 2020). The pLCA methodology is applied, and the Environmental Footprint (EF) 3.1 impact assessment method is used, including its characterisation and normalisation approaches (Andreasi Bassi et al., 2023; for set of used factors see Appendix Z, File VIII).

A scenario analysis, following the SIMPL approach by Langkau et al. (2023), is performed to establish scenarios for the different rates of technological advancement. Sensitivity analysis will explore how variations in key parameters affect the outcomes. Additionally, uncertainties related to future projections will be addressed through sensitivity analysis.

The geographical scope is focussed on the Netherlands, reflecting the location of the WM pump housing's end-use and relevant market conditions. The flowcharts in the inventory section illustrate system boundaries and cut-offs, detailing processes that are included and excluded from the assessment.

4.1.3. Functional Unit, Alternatives, Reference Flows

The functional unit for this study is "providing 12.5 years of washing machine pump use to a Dutch consumer under different future scenarios, assessed for 2025, 2030, 2040, and 2050." This time frame reflects the assumption that a spare pump should be able to keep a WM running for at least one full additional WM lifetime, forming a consistent basis for comparing the environmental impacts of different spare part provision strategies. Romania was chosen as the manufacturing location for IM pumps, as multiple major WM brands sold in the Netherlands (such as AEG, Samsung, and Miele) use pumps produced by Askoll and Hanning HEW, both of which have manufacturing facilities in Romania (Askoll, 2021; Hanning, n.d.; Statista, 2024). A storage time of 10 years was used, being in line with the Ecodesign measures by the European Commission demanding a spare part availability of 10 years minimum for WMs (European Commission, 2019). The SLA-printed pumps are assumed to be printed on demand within the Netherlands.

Table 4: Overview of functional unit, alternatives, and reference flows of the product systems.

	Functional Unit	
Functional Unit	Providing 12.5 years of washing machine pump use to a Dutch consumer under different future scenarios, assessed for 2025, 2030, 2040, and 2050.	
	Injection Moulding	**SLA Printing**
Alternative	Injection-moulded pump enclosure, produced in batches in Romania and stored in inventory for up to 10 years.	SLA-printed pump enclosure, produced on demand in the Netherlands.
Reference Flow	Providing 12.5 years of washing machine pump use with an injection-moulded enclosure, produced in batches in Romania and stored in inventory for up to 10 years, to a Dutch consumer under different future scenarios, assessed for 2025, 2030, 2040, and 2050.	Providing 12.5 years of washing machine pump use with an SLA-printed pump enclosure, produced on demand in the Netherlands, to a Dutch consumer under different future scenarios, assessed for 2025, 2030, 2040, and 2050.

4.2. Inventory Analysis

4.2.1. System Boundaries, Cut-offs, Multifunctionality, and Allocation

Economy-environment system boundary

This pLCA captures all economic flows from material extraction until their EoL stages. Consistent with Ecoinvent's system boundaries, environmental flows are defined as resources entering the economy from the natural environment (e.g., crude oil or natural gas before extraction) and emissions exiting into natural compartments (e.g., CO_2 emissions to air or pollutants to water). Treated outflows, such as wastewater and solid waste disposal, are modelled using the corresponding Ecoinvent processes to reflect real-world management.

Cut-offs

Due to time and data limitations, specific flows are excluded from this study. The following processes are consistently cut off for both product systems:

- **Factory buildings:** impacts from constructing and maintaining IM and SLA facilities.
- **Equipment assembly:** manufacturing and assembling IM machines and 3D printers.
- **Equipment maintenance:** routine maintenance activities for both IM and SLA equipment.
- **Transport packaging:** all packaging related to the transport of goods.
- **Pump installation:** energy consumption, consumables, and technician services required to replace a pump.
- **Consumables:** gloves, safety equipment, and cleaning supplies used in manufacturing.
- **Other pump components:** Only the pump housing is included; components such as the motor and wiring are excluded, as this study focuses on assessing the comparative impacts of IM versus SLA printing and their associated logistics and storage, not the entire pump system.

Multifunctionality and Allocation

This study does not encounter co-production processes. For the ABS open-loop recycling, consistent with the ecoinvent cut-off by classification approach, waste is considered the responsibility of the waste producer (ecoinvent, 2024). Therefore, all impacts of the recycling process steps are part of the primary system generating the waste, while subsequent use of the derived materials, such as recycled ABS, comes burden free.

4.2.2. Flowcharts

The following flowcharts (Figure 5 and Figure 6) show the product systems for both alternatives, including the system boundaries, goods, wastes, foreground, and background processes.

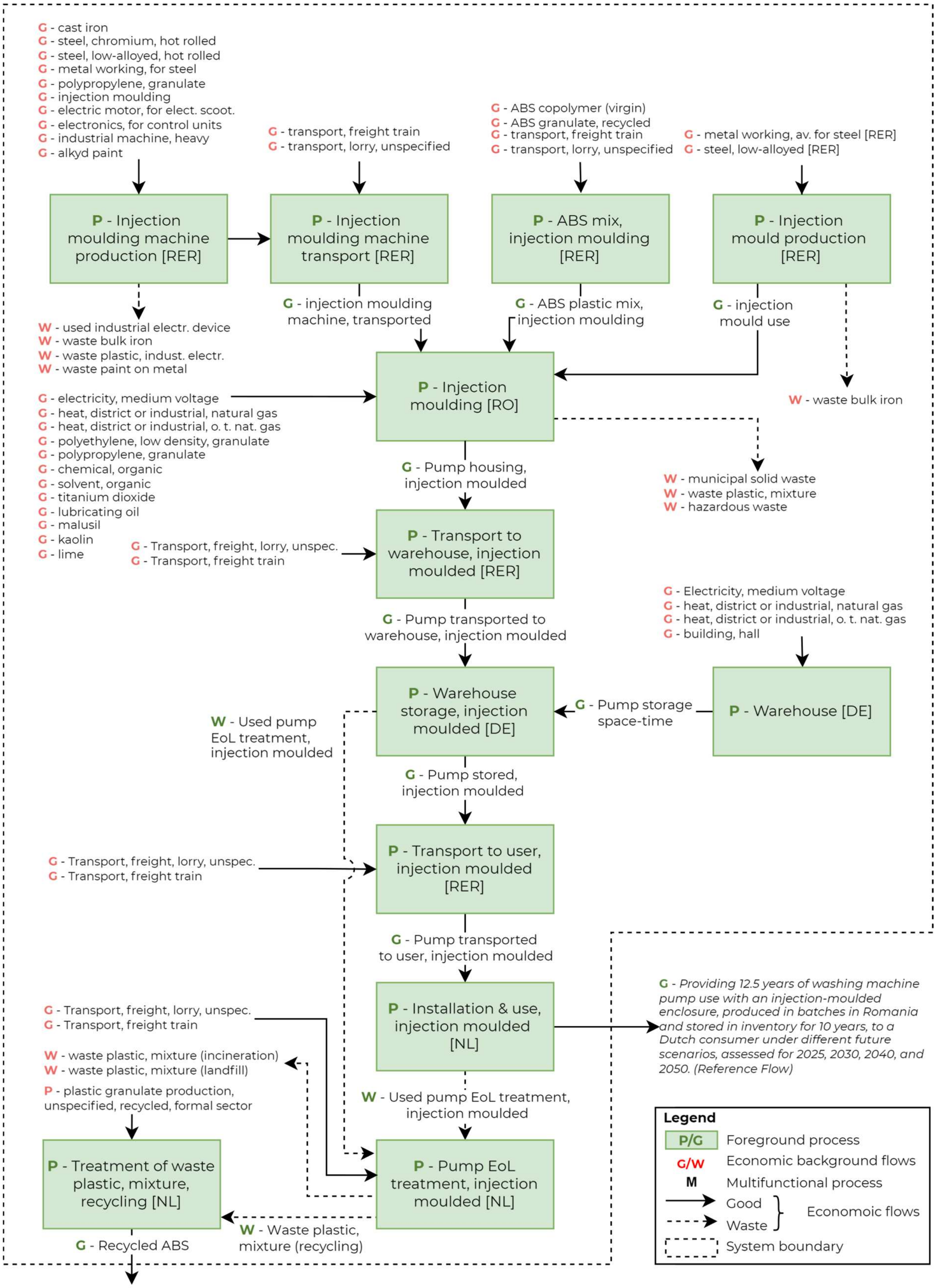

Figure 5: Flowchart of alternative 1, describing the processes and products required to produce one washing machine pump with an injection moulded chassis.

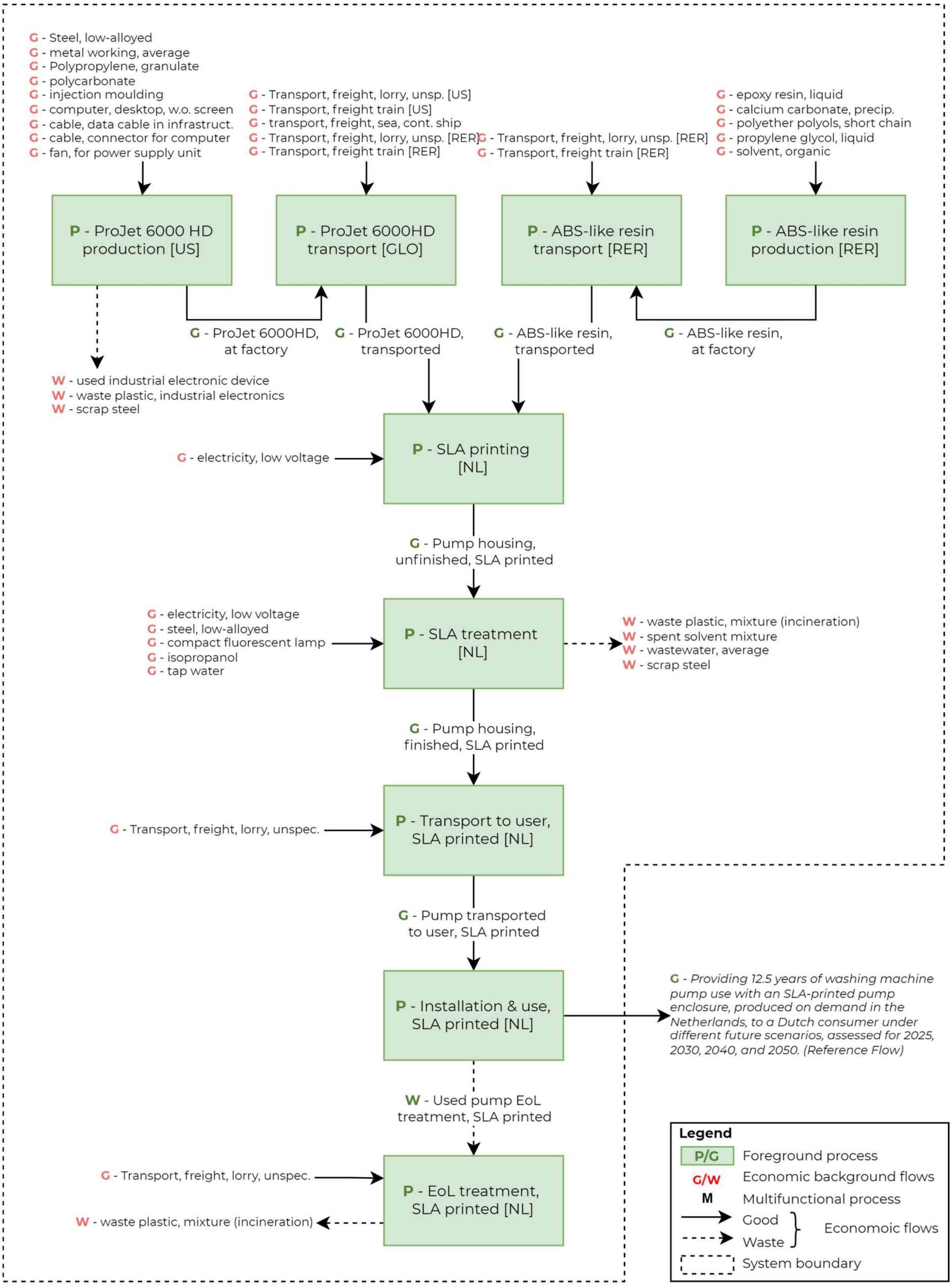

Figure 6: Flowchart of alternative 1, describing the processes and products required to produce one washing machine pump with an SLA printed chassis.

4.2.3. Data Collection and Unit Process Data

The IM process data is primarily derived from an LCA by Arburg on their IM machines and an adapted IM ecoinventprocess (Hirschier, 2024; Stern, 2022). In the case of SLA printing, the study leans on three primary data sources. The first source by Faludi et al. (2015) concerns inventory data for the production and printing process with ProJet 6000HD and the second by Shi & Faludi (2020) addresses assumptions regarding utilisation. The third by Mele et al. (2020) provides information on SLA treatment and other steps not covered by the study. While the latter focuses on home SLA printing, the data and assumptions have been adapted for commercial-scale SLA printing. The complete LCI dataset can be found in Appendix Z, File I which includes detailed calculations and data sources in File II.

The following sections, 4.2.4 and 4.2.5, outline the data points and formulas utilised to develop the LCI for the IM and SLA alternatives, along with their respective foreground processes. This data serves as the input for the current systems in 2025, which are held constant in the baseline scenario through 2030, 2040, and 2050, while only the background system changes according to the implementation of Premise transformation. Changes reflecting advancements in technology across various timesteps are detailed in Chapter 4.3.

4.2.4. Data Collection for Injection Moulding System

Injection Moulding Machine Production & Transport

The pump is assumedly produced using a medium-sized IM machine with a clamping force of 2000 kN (Arburg, 2024). It weighs 8,300 kg, has a material throughput of 16.2 kg of plastic per hour and is assumed to have an average lifespan of 10 years (ACO MOLD, 2014; Stern, 2022). Assuming it operates 24 hours per day, with 10% downtime for maintenance, 365 days a year for 10 years, it can produce approximately 1,280 tons of plastic. The machine attribution per kg of plastic is calculated by dividing it by its operational output over its lifespan, resulting in 7.83e-7 of machine per kg of plastic. Based on the inventory data provided by Arburg, their machines are composed of approximately 55% plastic-coated cast iron, 35% steel and sheet metal (which may be untreated, heat-treated, or plastic-coated), 7% plastic parts, drive components, and electronic elements, while 3% of the materials remain unaccounted for. The materials have been matched with cast iron and alkyd paint for the metal coating, a mix of 50% low alloyed hot rolled steel and 50% hot rolled chromium steel, all treated using average metal working for steel. The remaining 7% of components comprises 2.3% polypropylene with IM, 2.3% electronics for control units, and 2.3% electric motors for electric scooters. The unspecified 3% have been approximated with a heavy industrial machine. The IM machine is transported from its manufacturing location in Loßburg, Germany, to Romania, covering approximately 1,600 km. The weight of the transported items is assumed to be 1.5 times the weight of the actual machine, similar to the transported weight increase of the SLA printer, to account for additional packaging and protection. At the EoL, the machine components undergo treatment, split into waste bulk iron, waste plastics from industrial electronics, electronics scrap from control units, used industrial electronic devices, and waste paint on metal.

ABS Mix

The thermoplastic material under consideration is acrylonitrile-butadiene-styrene (ABS) copolymer. In the base scenario, it is assumed that the formulation consists entirely of 100% virgin plastics, as the current usage of plastic recyclate in the EU remains low, ranging between 8-12% (Bergsma et al., 2022; Cyclpac, 2020). Furthermore, the utilisation of recyclate in ABS is expected to be even lower, given that approximately 85% of ABS produced is incinerated or landfilled within the EU (European Commission, 2022). This is primarily due to the presence of additives and fillers that complicate the recycling process (European Commission, 2022). In the improved scenario, virgin ABS is progressively replaced with recycled ABS. In accordance with the ecoinvent cut-off system model, the recycled granulate is burden-free, and only transport impacts are accounted for. The projected transport distance to Romania is 1500 km, based on the assumption that recycling occurs at a centralized location within the EU. Consequently, the transport requires 1.5 ton*km per kilogram of recycled ABS granulate transported. Both scenarios take into consideration the impacts associated with transportation.

Injection Mould Production

The pump consists of four primary sub-components, with their dimensions being based on the disassembled reference pump. The actual mould dimensions are larger than the to-be-manufactured part to accommodate for material shrinkage, mould walls, runner systems, cooling channels, and ejection systems and also depend on the number of cavities, part orientation and overall complexity (Poli, 2001). To accommodate for these factors, 10 cm are added in each dimension of the sub-components bounding box to approximate the mould size. The total mould volume is calculated to be about 23,000 cm^3 and using a steel density of 7.85 g/cm^3, the total weight of the mould parts is estimated at 180 kg. Based on an assumed production run of 50,000 pumps (the mould's lifetime), 0.018 kg of steel is attributed per kg of produced plastic. The mould production is modelled using low alloyed steel, the closest material proxy for class 103 or 104 moulds (Ye, 2023). Also included are average steel metal working from ecoinvent for the milling, including transportation and EoL treatment. The formula for mould use per kg of plastic is:

Equation 1:

$$Injection\ Mould\ Use\ per\ kg\ of\ Plastic\ (kg) = \frac{Mould\ Volume\ (m^3) \times Steel\ Density\ (kg/m^3)}{Mould\ lifetime\ (cycles)} \times \frac{1\ (kg)}{Part\ Weight\ (kg)}$$

Injection Moulding

The IM data is based on ecoinvent's IM process, representing the average inputs and outputs for IM in Europe, including energy consumption and other inputs such as lubricants and chemicals. Packaging and factory inputs have been cut off for consistency between the two alternatives. Additionally, the specified plastic mix, IM machine, and mould are included in the inputs. It has been scaled to the production of 1kg of pumps, with the later process using 0.2kg of pump IM to reflect the production of one pump.

Transport to Warehouse & User

The pump's first transport stage is from the factory in Romania to the warehouse in Germany, with an approximate 1500 km transport distance, resulting in 0.3 ton-kilometres. The final transport from Germany to the user in the Netherlands is assumed to be 500 km, resulting in 0.1 ton-kilometres. A market mix of unspecified lorries, consisting of different sizes and EURO emission standards, is used for both stages.

Warehouse & Storage

The pump is assumed to be stored for an average of 10 years in a warehouse located in Germany. The warehouse is based on the "market for building hall" from ecoinvent and has a size of 50×30×7 meters (length, width, height), a floor area of 1500 m^2 and a total volume of 10500 m^3. Assuming 80% utilisation of the space, the actual storage capacity is 8400 m^3, leading to a total lifetime storage capacity of 420,000 m^3*years (based on ecoinvent's assumed service life of 50 years). Annual energy consumption for non-refrigerated warehouses is about 56.66 kWh/m^2 for electricity and 144236 Btu/m^2 for heat (Meteor Space, 2024). The energy use per m^3 of usable space per year is calculated as follows:

Equation 2:

$$Energy\ use\ per\ m^3\ per\ year\ (kWh/m^3/year) = \frac{Energy\ use\ per\ m^2\ per\ year\ (kWh/m^2/year)\ \times\ Total\ floor\ area\ (m^2)}{Actual\ storage\ capacity\ (m^3)}$$

Given a pump storage volume of 0.004 m^3, the energy use per pump per year is 0.0469 kWh of electricity and 0.1087 MJ of heat and is calculated as follows:

Equation 3:

$$Energy\ use\ per\ pump\ per\ year\ (kWh/pump/year) = Energy\ use\ per\ m^3\ per\ Year\ (kWh/year) \times Pump\ storage\ volume\ (m^3)$$

The fraction of warehouse capacity used by a pump for one year is determined by dividing the pump's storage volume by the total lifetime storage capacity. The corresponding floor area allocation is obtained by multiplying this fraction by the total floor area of the warehouse.

Equation 4:

$$Floor\ area\ attribution\ per\ pump\ per\ year\ (m^2/pump/year) = \frac{Pump\ storage\ volume\ (m^3)}{Total\ lifetime\ storage\ capacity\ (m^3 * years)} \times Total\ floor\ area\ (m^2)$$

This results in an annual energy consumption of 0.0469 kWh of electricity and 0.1087 MJ of heat, and a floor area attribution of 1.43e-5 m^2 per pump per year. To derive the necessary storage inputs, these values are multiplied by the number of years the pump is stored, which in this case is assumed to be 10 years, as explained earlier. While this does not reflect the average duration of spare part storage due to variability of demand (likely between the typical 1-2 year WM warranty and the 12.5-year average WM lifetime), it examines the implications of the Ecodesign Measures, which require a minimum WM spare part availability of 10 years (European Commission, 2019). A sensitivity analysis is carried out to assess whether storage duration significantly affects the overall impacts.

Spare Part Overproduction

To align with the Ecodesign Measures, this study introduces an overproduction factor to address the inherent uncertainties associated with long-term demand forecasting. Manufacturers must determine the size of the final production run to satisfy potential future demand for spare parts by deploying forecasting models (Kim et al., 2016). Forecasting models exhibit a wide range of accuracy, as expressed, for example, by the Mean Absolute Percentage Error (MAPE) metric, where e.g. when having a 10% higher and a 10% lower estimate than the actual demand, it results in a MAPE of 20% (Roberts, 2023). Typically, forecasts with a MAPE below 10% are considered highly accurate, those between 10% and 20% are categorized as good, 20% to 50% are deemed reasonable, while forecasts exceeding 50% are labelled as inaccurate (Lewis, 1982). Hemeimat et al. (2016) reported for example errors of approximately 12% for fast-moving parts, 17% for slow-moving parts, and up to 33% for non-moving parts. Additionally, research by Kim et al. (2016) in the field of auto parts remanufacturing reveal errors ranging from around 12.7% for stable demand scenarios to as high as 65% in conditions of fluctuation. Considering the lack of specific data pertaining to WM pumps and considering the prolonged 10-year forecast horizon, a prediction error of 20% is assumed. For modelling, this implies that suppliers must overproduce spare parts to guarantee their constant availability. Consequently, the inputs and outputs for warehouse storage are scaled by a factor of 1.2; this means that the production of one functional pump necessitates the creation of 1.2 pumps, along with 12 pump-years of storage and 0.2 kg of pump EoL treatment for the unused part.

Installation & Use

The installation requires replacing the original pump. Energy consumption and emissions associated with the installation are considered negligible and are therefore not included. The new pump operates within the WM without any additional direct energy usage attributed to it; therefore, its impact is limited to its functional contribution of 12.5 years to the operation of the WM. At the EoL, the replacement pump enters the pump EoL treatment process. The original pump that is being replaced is not within the system boundary of this study.

EoL Treatment

To derive the EoL recycling split for ABS, data from the European Commission (2022) and Plastics Europe (2022) were synthesized and adjusted to account for the specific characteristics of ABS waste management. The European Commission reports that 85% of ABS is currently incinerated or landfilled in the EU, implying a maximum recycling rate of 15%, which is assumed as the baseline for recycling. As the European Commission did not declare the split between incineration and landfill, data by Plastics Europe on the breakdown of electronic plastic waste streams was used. They found a split of 48% incineration with energy recovery and 27% landfill. While they reported a 25% recycling share, the 15% of the European Commission is assumed to be the more realistic value, given the lower collection and recycling rates of ABS specifically. Consequently, the final waste management split for ABS was calculated as 15% recycling, 54% incineration, and 31% landfill. Transportation to the treatment facilities is based on the 0.0688 ton*kilometres per one kg of plastic from the Dutch market for waste plastic mixture, implying an average transport distance of about 69km.

To accurately attribute the impacts of recycling to this product system, the recycling process impacts of “Treatment of waste plastic, mixture, recycling” are modelled by using the “plastic granulate, unspecified, recycled” from “plastic granulate production, unspecified, recycled, formal sector” as inflow. Although this modelling approach visually suggests a direct input of recycled plastic granulate into the recycling process, it is anticipated to produce similar results as modelling a separate recycling process that factors in all necessary inputs from the previous treatment steps (sorting, shredding, grinding, and granulate production). This method is presumed to fairly allocate the EoL treatment impacts of recycling to the primary product system, with the recycled granulate considered burden-free, in line with the cut-off system model by ecoinvent. While this approach does not perfectly align with data on plastics recycling in the European Union, given that it relies on data from India, it remains the only suitable plastic recycling process within ecoinvent v3.10.1.

4.2.5. Data Collection for SLA Printing System

PoJet 6000HD Production & Transport

Based on measurements by Faludi et al. (2015), the ProJet 6000HD SLA printer by 3D Systems weighs 181 kg and is composed of 89% steel, 4% polypropylene, 4% electronics (motors, computer, wires, fans), 2% Polycarbonate, and 2% glass. Manufacturing includes material processing of the plastic and steel inputs using IM and average metal working. The energy consumption of the assembly process is excluded. For shipping, the printer is assumed to be manufactured in Rock Hill, USA (3D Systems headquarters), with a crated transport weight of 272 kg (3D Systems, 2024). Transport involves 290 km by lorry to the port in Charleston, 7130 km by ocean freight to Rotterdam, and 150 km by truck to its destination in the Netherlands. At its EoL, the printer is assumed to be dismantled, and the components are going to their relevant treatment processes in Europe.

ABS-like Resin Production & Transport

The resin composition is based on the material safety data sheet by 3D Systems (2014)for Accura ABS-like Resin, and the functions of the materials have been identified based on Voet et al. (2021), and matched to similar materials in ecoinvent. Compared to the previous studies that treated the resin as a single chemical as in Faludi et al. (2015), providing only lower and higher estimates (based on scenarios involving 100% epoxy resin versus acrylic acid), or Mele et al. (2020) who assumed a simple two-component mix (i.e. 99% methacrylate oligomers and monomers with 1% diphenylphosphine oxide), this approach aims to give more accurate results. In the final recipe, 55% is assumed to be epoxy resin as the polymer base, 15% polyether polyols as a reactive diluent, 5% organic solvent as a photoinitiator, and 5% propylene glycol as a proxy for additives. Calcium carbonate was used to proximate the missing 12% in the datasheet and represents fillers and other additives. The resin is assumed to have been manufactured in Europe and transported for about 800 km to the printing facility, resulting in 0.001 ton*km per kg of resin.

SLA Printing

To allocate printer impacts and electricity use per printed part, an average printer lifetime of 5 years and continuous operation (90% uptime, 10% maintenance and repair) were assumed, following Faludi et al. (2015). According to their study, the printer consumes 280.8 W during printing and 258.5 W while idle. The resin pump weight is also estimated at 0.2 kg, given the similar material density of ABS and the resin and likely material savings from SLA printing over IM. Based on the build chamber dimensions (25×25×25 cm), an estimated maximum of 5-6 pumps could be printed simultaneously, with two pumps printable side by side at 9 cm height. For further utilisation calculations, one pump is assumed to use half the print bed and has a build height of 9cm.

Estimating the print time was challenging without a 3D model or proprietary slicing software, given the scope of this study. Unlike with DLP printing, where print speed is mainly related to the number of layers/object height as each layer is exposed simultaneously, SLA print time also depends on the laser head's movement, increasing time with more parts. However, this is not proportional to mass, as can be understood from the data in the study by Faludi et al. (2015), where a solid and shelled part was printed. While in this case, the mass increased by 4.88 times, the time increased only 1.47 times. The solid part weighs 72g, has a height of 3 cm, and takes 5.13 hours to print (1.711 hours/cm). Given that the pump weighs 200g, has a height of 9 cm, and has a similar mass per cm as the solid reference part of Faludi et al. (2015), it has been estimated that printing one pump will take approximately 15.4 hours.

Equation 5:

$$Print\ time\ one\ pump\ (hours) = \ Pump\ height\ (cm) \times \left(\frac{Print\ time\ reference\ part\ (hours)}{Part\ height\ reference\ part\ (cm)}\right)$$

The print time for two pumps, side by side, is influenced by the total number of parts. Assuming efficient laser pathing, a 25%-50% increase in time could be expected, with a medium value of 35% used in calculations. This results in an approximate print time of 20.8 hours for two pumps.

Equation 6:

$$Print\ time\ two\ pumps\ (hours) = Print\ time\ for\ one\ pump\ (hours) \times (1 + Efficiency\ factor)$$

Using energy consumption data, print time for two pumps, Faludi's average cleanup time of 0.033 hours, and the number of parts per batch, the energy required per pump is approximately 2.92 kWh. To allocate the printer's impact to a single pump, the printer's operational time has to be calculated. Assuming daily operation for 21.6 hours (accounting for maintenance), it can produce about 2.1 pumps daily.

Equation 7:

$$Pumps\ printed\ per\ day\ (units/day) = \frac{Daily\ printing\ hours\ (hours)}{Print\ time\ for\ two\ pumps\ (hours) + Setup/cleanup\ time\ (hours)} \times Pumps\ per\ batch\ (units)$$

Over a 5-year lifetime, it can print approximately 3,786 pumps, resulting in the attribution of 2.6e-4 printers per pump. The share of printer impact allocated to each pump is determined by dividing one printer by the total number of pumps produced. Resin inputs are based on the part's mass, with an additional 8% of the pump weight needed as support structures, requiring about 17 g of extra resin.

SLA Treatment

After printing, the parts are cleaned in an immersion bath of first isopropyl alcohol (IPA) and a second bath with water using the ProJet Part Washer System (3D Systems, 2011). The system consists primarily of steel, and inputs have been estimated based on the external dimensions (76×34×61 cm) and the estimated amounts of extra sheets needed to form the two tanks. Assuming a steel thickness of 1.5mm and material density of 7.75 g/cm^3, the bath uses about 27.2 kg of steel. Given its low complexity, the washing station is assumed to last for about 10 years. With daily operation and assuming an average of 20 parts cleaned daily, the washer can clean 73,000 pumps over its lifecycle, allocating 0.0004 kg of steel per pump and the corresponding EoL treatment.

Equation 8:

$$Washing\ station\ per\ pump\ (kg/unit) = \frac{Steel\ surface\ (cm^2) \times Steel\ thickness\ (cm) \times Steel\ material\ density\ (g/cm^3)}{Daily\ cleaned\ parts\ (units) \times Yearly\ days\ of\ operation\ (days) \times Years\ of\ operation\ (years)}$$

For the IPA and water attribution per part, the tank volumes (37.85L IPA, 38L water) were divided by the estimated number of parts cleaned per tank. Since 3D Systems did not provide an estimate, the assumption of 200 parts cleaned per tank by Mele et al. (2020) was used. Based on the material densities (0.786 g/cm^3 for IPA and 1 g/cm^3 for water), 0.15 kg of IPA and 0.19 kg of water are attributed per pump. Liquid production and disposal impacts are included.

Equation 9:

$$Liquid\ weight\ per\ cleaned\ pump\ (kg/unit) = \frac{Volume\ of\ liquid\ (litres) \times Material\ density\ (g/cm^3)}{Parts\ cleaned\ per\ tank\ (units)}$$

The parts are then cured under a UV light in the ProJet Part Curing Unit. It is also made of steel, and the same calculation steps were performed as for the washing unit based on the station's external measurements (42×42×41 cm), resulting in a steel weight of 14 kg. Given an approximate curing time of 1 hour, as recommended by 3D Systems (2022), two pumps can be cured simultaneously, and daily operation over 10 years can cure 48 pumps in a day or 175200 pumps in its life. Therefore, 0.0001 kg of steel and the appropriate waste treatment must be allocated per part.

Equation 10:

$$Pumps\ cured\ per\ oven\ life\ (units) = \frac{Daily\ operational\ hours\ (hours) \times Days\ of\ operation\ (days) \times\ Pumps\ per\ batch (units)}{Curing\ time\ (hours)}$$

The Part-Curing Unit uses fluorescent UV bulbs, which are replaced every 1600 hours. Assuming each bulb weighs 60g and with two pumps cured per cycle, the impact of bulb use is distributed among the total cured pumps over the bulb's lifetime, resulting in 0.0006 bulbs allocated per pump.

Equation 11:

$$UV\ bulbs\ per\ cured\ pump = \frac{Bulbs\ per\ oven\ (units)}{\left(\frac{Life\ expectancy\ of\ bulb\ (hours)}{Curing\ time\ (hours)}\right) \times Pumps\ cured\ per\ cycle\ (units)}$$

Transport to User

The final transport of the pump to the user is assumed to be by lorry over 150km.

Installation & Use

Installation energy inputs are assumed to be negligible, like for the IM pump.

EoL Treatment

At its EoL, the pump is assumedly incinerated using the municipal incineration process for waste plastic treatment, as it cannot be recycled due to it being a thermoset plastic. Transportation for waste disposal adds 0.01376 ton-kilometres, based on the transport distances used in the market for waste plastic in the Netherlands.

4.3. Scenario Development

For each of the two alternatives, three scenarios are modelled: the first, named "Base," assumes that the foreground processes remain unchanged and only the background system (such as the electricity mix) undergoes transformations, illustrating a business-as-usual scenario. Furthermore, two scenarios are modelled with additional adjustments to the foreground processes driven by anticipated advancements in technologies, supply chains, and policies, with one representing moderate enhancements ("Realistic") and the other showcasing a more aggressive improvement approach ("Ambitious"). The parameters were selected based on literature recommendations and observations from the initial LCIA results, highlighting the processes and goods that significantly contributed to the overall impact. For IM, the implemented parameters are recycling inputs, transport, machine energy efficiency, overproduction, and EoL improvements. While for SLA the selected parameters were resin impact, printer lifetime, printer efficiency, post-processing efficiency (solvent use and curing efficiency), and transport.

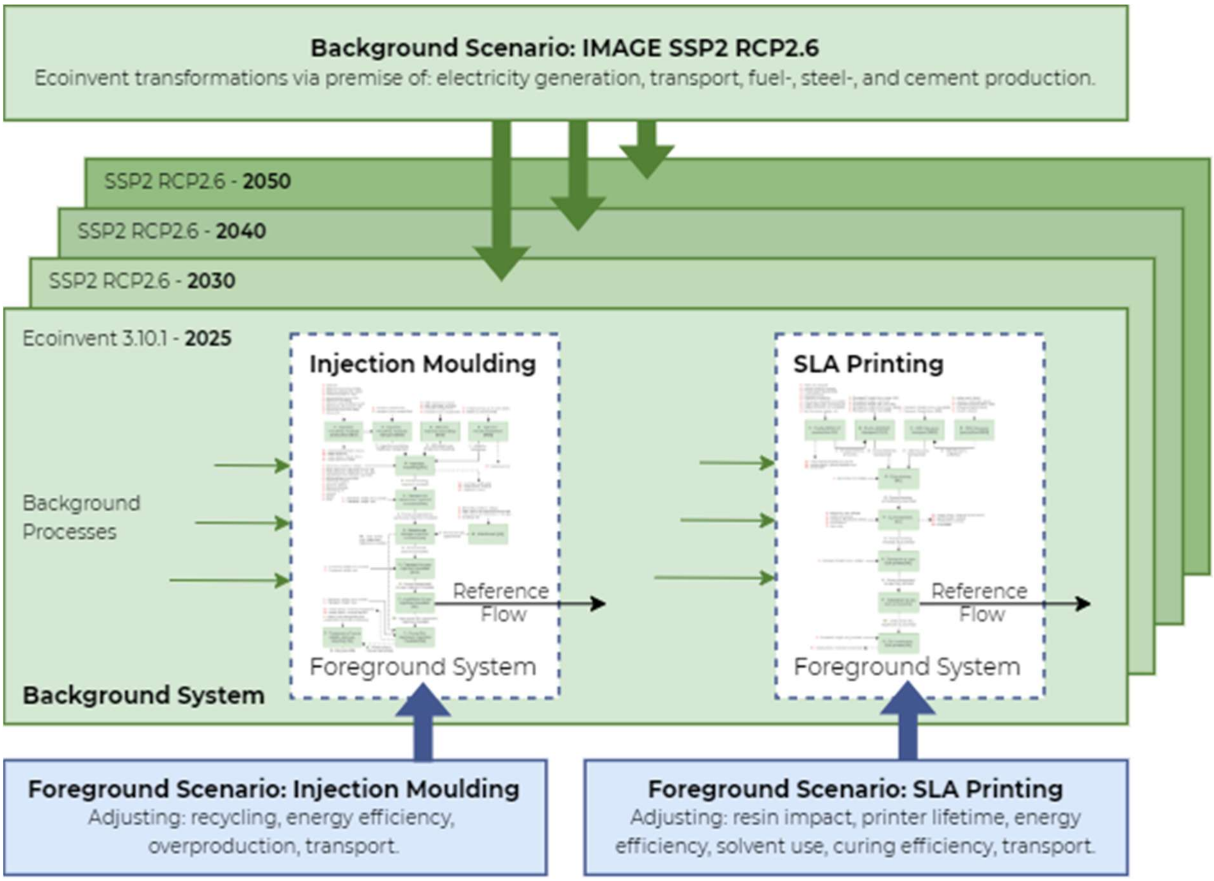

Figure 7: Simplified flowchart of the two product systems and the for- and background sceanrios. Figure adapted from Müller et al. (2024).

4.3.1. IM Scenarios

Recycling Inputs Share

While the use of recycled plastic inputs is increasing in the EU, current adoption rates remain low due to quality concerns and limited availability, comprising only 8-12% of all plastic consumption (Bergsma et al., 2022; Cyclpac, 2020). The EU's Circular Plastic Alliance aims for an 18% recyclate use by 2025, with Plastics Europe suggesting a target of 30% for recycled inputs in packaging and the Netherlands pursuing an ambitious 41% recyclate input share by 2030 (Bergsma et al., 2022). However, most recyclate is produced from packaging, while the primary demand is for non-packaging applications, accounting for up to 74% of total consumption (Bergsma et al., 2022;

European Environment Agency, 2022). These products often require different polymers or complex mixtures, complicating the recycling of these materials and making them more costly, limiting the availability of recycled plastics such as ABS (European Environment Agency, 2022). Therefore, the recycling share of inputs here is likely lower than the EU average, and for the base year of IM, a 0% share of recycled granulate input is assumed. Growth in recyclate use in these sectors is expected to be slower than in packaging, given the challenges of recycling and the limited supply of materials due to the typically longer lifespan of non-packaging products. Hence, the assumed recycling shares are 10%, 20%, and 30% by 2030, 2040, and 2050 respectively, for the "realistic" improvement scenario, and 30%, 45%, and 50% for the more "ambitious" scenario. It should be noted that achieving a recyclate usage of 40% in the Netherlands by 2030 would necessitate a collection rate of 95%, which is highly ambitious, according to Bergsma et al. (2022).

Transport Modes

To determine the modal split for the transportation of the pump from Romania to Germany, the modal split for freight transport in the EU must be examined. According to Eurostat (2022), 78% of all freight was transported by lorry, 17% by rail, and 5% by waterways in 2022, leading to a modal split of 82% for road transport and 18% for rail when excluding waterways. Based on the Fit For 55 MIX scenario by the JRC, the modal split for 2030 is projected to be 67.6% for road, 20% for rail, and 12.4% for waterways (European Environment Agency, 2024). Excluding water transport from the scenario results in a modal split of 77% for road and 23% for rail in 2030. The share of rail transport is therefore assumed to start at 20% in 2030, increase to 30% in 2040, and 35% by 2050 for the realistic scenario. In the ambitious scenario, the transition is expected to be quicker, with the rail share reaching 30% by 2030, 45% by 2040, and 50% by 2050, indicating a significant shift towards rail as intended in an EU white paper from 2011. While this was initially the intended goal of EU policy, research by Tavasszy (n.d.) concluded that this is very unrealistic, and current trajectories indicate the share to be much lower, making it a reasonable base estimate for the ambitious scenario.

IM Machine Energy Efficiency

Although IM is a well-established technology, there remains potential for efficiency improvements that could lead to reductions in energy consumption over the coming decades. The specific electricity consumption of IM machines is influenced by various factors, including the type of material used, part geometries, and machine utilisation; however, it is also strongly correlated with overall material throughput (Cardeal, 2016; Elduque et al., 2018). Cardeal (2016) identified that machines with high clamping force (typically associated with hydraulic machines), which affects throughput, do not always correlate proportionally with lower energy consumption. Instead, the relationship between machine size and efficiency is nonlinear, underscoring the critical roles of machine design and utilisation (Cardeal, 2016; Elduque et al., 2018). One strategy for enhancing IM energy efficiency involves transitioning from traditional hydraulic systems to hybrid or fully electric IM machines (Global Market Insights, 2024). Both Elduque et al. (2018) and Arburg (2022) have demonstrated that fully electric machines exhibit lower electricity consumption compared to their hydraulic counterparts. Given that the selected Arburg machine model, the "Allrounder 470 H," is a hybrid, there is an opportunity for further improvement by switching to a fully electric model. Elduque et al. (2018) also reported significant discrepancies between actual measured electricity consumption and the default values provided by ecoinvent, suggesting that standard datasets may not accurately capture real-world variations. Nevertheless, due to the early assessment stage of this study and the need for comparability with existing research, the default ecoinvent value for IM energy consumption will be utilised as the baseline. In addition to optimising machine selection, further energy reductions could potentially be achieved through enhanced utilisation and optimised throughput/cycle times. Thus, in a realistic scenario, a moderate increase in energy efficiency is modelled, projecting a 5% reduction in energy consumption relative to the current standard by 2030, 10% by 2040, and 15% by 2050. In the ambitious scenario, energy consumption is expected to decline by 15% by 2030, 25% by 2040, and 30% by 2050.

Overproduction
Overproduction primarily arises from uncertainty in demand forecasting. Improved prediction algorithms, based on better data collection regarding products in use and failure rates, may reduce these uncertainties. In the literature, there are only comparisons of the prediction errors of current algorithms, which mostly focus on shorter-term demand predictions. Consequently, estimates about the potential for future improvement of these algorithms had to be made. It is assumed that, in a realistic scenario, overproduction will decrease from 20% in 2025 to 17%, then to 13%, and finally to 10% by 2050. Meanwhile, in an ambitious scenario, reductions to 13% by 2030, 8% by 2040, and 5% by 2050 are assumed to be achieved.

EoL Recycling Share
Recycling rates are expected to improve through enhanced sorting and advancements in mechanical and chemical recycling technologies, though infrastructure challenges may hinder progress. With no clear EU policies on recycling rates for non-packaging plastics and the added complexity of recycling ABS, future recycling shares needed to be estimated. The realistic scenario assumes EoL recycling rates of 25% by 2030, 35% by 2040, and 40% by 2050, while the ambitious scenario targets 40% by 2030, 55% by 2040, and 60% by 2050. For both scenarios, the landfill share is projected to decrease to 0% from 2030 onwards, in compliance with EU regulations that ban this practice starting in 2030, with the remaining unrecycled plastic expected to be incinerated (European Commission, 2018)

4.3.2. SLA Scenarios

Resin Recipe Impact Reduction
Since SLA printed parts are made from thermoset plastics and primarily utilise resins derived from fossil-based acrylates and epoxides, they currently lack re-processability and (bio-)degradability, which significantly limits their sustainability (Maines et al., 2021; Voet et al., 2021). Therefore, improving the formulation is a crucial factor in reducing the overall environmental impacts of SLA printing. Voet et al. (2021) noted that recent studies focus on resins derived from renewable sources, some partially degradable and others investigating repairable or recyclable technologies. However, fully recyclable or biodegradable resins are not yet available. Given the absence of projections regarding the development of resins, estimates were necessary. In both scenarios, rather than modelling alternative bio-based resins with highly uncertain actual formulations, resin improvements are modelled as reductions in inputs to the printing process. The "realistic" scenario projects resin impact reductions of 10% by 2030, 20% by 2040, and 30% by 2050, while the "ambitious" scenario anticipates reductions of 20%, 35%, and 50%. Realistically, an absolute reduction of impacts is unlikely, as substituting impactful materials with biobased alternatives will likely shift those impacts; however, overall impact reductions of the recipe are considered plausible.

Printer Energy Efficiency
A key factor determining the sustainability of SLA printing is its energy consumption, determined by the light source and its efficiency, as well as the power draw of the motors, control electronics, and temperature control systems that maintain consistent resin conditions. Since the print speed directly influences the energy allocated per part, enhancing speed via improved light sources and

optimised exposure strategies can significantly reduce energy impacts per part. However, as Gutowski et al. (2017) demonstrated, increasing light source power for faster print speeds eventually leads to diminishing returns due to the higher energy demands. Therefore, improvements must encompass not only light source power increases but also optimising laser pathing. In addition, Shi & Faludi (2020) highlighted that optimising print bed utilisation is crucial for SLA, given that the print time does not scale linearly with the printed mass. Considering these trade-offs, print energy reductions are assumed to be 10%, 20%, and 30% in a realistic scenario, and 20%, 40%, and 60% in an ambitious scenario. This reflects improvements through higher laser efficiency, optimized laser pathing, and enhanced print bed use while balancing the trade-offs between increased power draw and overall energy savings.

Printer Lifetime
Due to the long printing times and the estimated short lifespan of five years for the printer based on Faludi et al. (2015), the attribution per part is comparatively high, resulting in more significant environmental impacts per printed pump compared to an IM machine that, despite requiring more material inputs, has relatively low impacts per part due to its long lifespan and high production rate. Faludi et al. (2015) noted that, in addition to some surveys reporting short lifespans of just three years, they also found lifetimes of up to ten years in the literature, leading to their average assumption of five years. For the scenarios, it is assumed that improved maintenance, better design for repairability, and more durable components can increase the lifespan to 7, 9, and 10 years for the realistic scenario, and 10, 13, and 15 years for the ambitious scenario.

Post-Processing
In the post-processing phase, the solvents significantly contribute to the overall impacts based on the preliminary impact assessment, alongside small yet notable effects on electricity consumption for curing. Adopting low-solvent cleaning methods may assist in reducing hazardous waste. Due to the limited literature available, the improvement is modelled here as a decrease in solvent use. In the realistic scenario, reductions of 10%, 20%, and 30% are projected until 2050, while in the ambitious scenario, solvent usage is expected to decline 20%, 35%, and 50% by 2050. During the curing process, transitioning to energy-efficient UV LEDs instead of traditional bulbs may improve both energy consumption and lifespan. Given the minimal contribution of the light itself to the impact, reductions are modelled only by decreasing energy consumption by 20%, 30%, and 40% in the realistic scenario and by 35%, 50%, and 70% by 2050 in the ambitious scenario.

Transport Mode
Due to the decentralised production of SLA, the pumps' transport to the consumer contributes only marginally to the overall impacts. Therefore, and because shifting transport to rail for last-mile delivery is unlikely, transport improvements apply only to the distribution of printers and resin. For consistency, the same rail shares as for the IM scenarios are used.

4.3.3. Scenario Parameters Overview

Table 5 displays the complete set of scenario parameter changes, which are implemented in the model through a scenario difference file. The flow adjustments can be found in Appendix Z, File III.

Table 5: Injection moulding and SLA printing parameters change over time for improved scenarios.

	Parameter	2025	2030	2040	2050
IM Realistic	**Recycling inputs**	0% recycled	10% recycled	20% recycled	30% recycled
	Machine energy efficiency	Current standard	5% more efficient	10% more efficient	15% more efficient
	Overproduction	20%	17%	13%	10%
	Transport rail share	0% rail	20% rail	30% rail	35% rail
	EoL recycling and landfill	15% recycling 31% landfill	25% recycling 0% landfill	35% recycling 0% landfill	40% recycling 0% landfill
IM Ambitious	**Recycling inputs**	0% recycled	30% recycled	45% recycled	50% recycled
	Machine energy efficiency	Current standard	15% more efficient	25% more efficient	30% more efficient
	Overproduction	20%	13%	8%	5%
	Transport rail share	0% rail	30% rail	45% rail	50% rail
	EoL recycling and landfill	15% recycling 31% landfill	40% recycling 0% landfill	55% recycling 0% landfill	60% recycling 0% landfill
SLA Realistic	**Resin impact reduction**	ABS-like resin, 0%	10% lower impact	20% lower impact	30% lower impact
	Printer lifetime	5 years	7 years	9 years	10 years
	Printer energy efficiency	Baseline	10% more efficient	20% more efficient	30% more efficient
	Solvent use reduction	Baseline	10% reduction	20% reduction	30% reduction
	Curing efficiency	Baseline	20% less electricity	30% less electricity	40% less electricity
	Transport rail share	0% rail	20% rail	30% rail	35% rail
SLA Ambitious	**Resin impact reduction**	ABS-like resin, 0%	30% lower impact	45% lower impact	50% lower impact
	Printer lifetime	5 years	10 years	13 years	15 years
	Printer energy efficiency	Baseline	20% more efficient	40% more efficient	60% more efficient
	Solvent use reduction	Baseline	20% reduction	35% reduction	50% reduction
	Curing efficiency	Baseline	35% less electricity	55% less electricity	70% less electricity
	Transport rail share	0% rail	30% rail	45% rail	50% rail

4.4. Impact Assessment

The LCIA was conducted for the reference year 2025 using the untransformed ecoinvent database and for the years 2030, 2040, and 2050 with the transformed background databases and incorporating additional foreground flow scenarios in the Activity Browser. The EF3.1 impact assessment family was utilised, along with its corresponding normalisation and weighing factors. Normalisation results were derived by dividing the characterised impact by the normalisation factor, while the weighted results were obtained by multiplying these results by the factor and then summing them to arrive at a final single score.

5. Results

This section presents the LCIA results of the prospective LCA for WM spare parts produced via IM and on-demand SLA printing. For clarity, impacts for the 2030 and 2040 timesteps have been omitted in some visualisations but are available in LCIA results for all years in Appendix Z, File IV.

The results are divided into four sections:

1. **Impact assessment results:** Relative LCIA results showing impacts of both alternatives across impact categories and weighted and normalised results offering context for the magnitude of these impacts in different scenarios.
2. **Environmental hotspots:** identifying life cycle stages that contribute the most.
3. **Sensitivity analysis:** identifying the most influential scenario parameters and the effect of key modelling assumptions.
4. **Consistency & completeness:** verify consistency and completeness of the model.

5.1. Impact Assessment Results

5.1.1. Relative & Normalised Impacts in 2025

Relative Results

Figure 8 illustrates the results of impact indicators for each alternative in 2025, with the worst-performing alternative set at 100% for each category. SLA printing shows greater impacts across most categories compared to IM, particularly in freshwater ecotoxicity, carcinogenic and non-carcinogenic human toxicity, land use, material resource use, and ozone depletion, where IM only exhibits 11–26% of the impacts seen in SLA. For particulate matter formation, energy resource use, climate change, freshwater eutrophication, and ionising radiation, IM demonstrates impacts ranging from 54% to 92% of SLA's values. Water use is the sole category where SLA's impact is lower (by 9%) than that of IM. The relative impact results for future scenarios in 2050 remain consistent between the alternatives (see Appendix B), with IM displaying lower impacts than SLA in all categories except for water use.

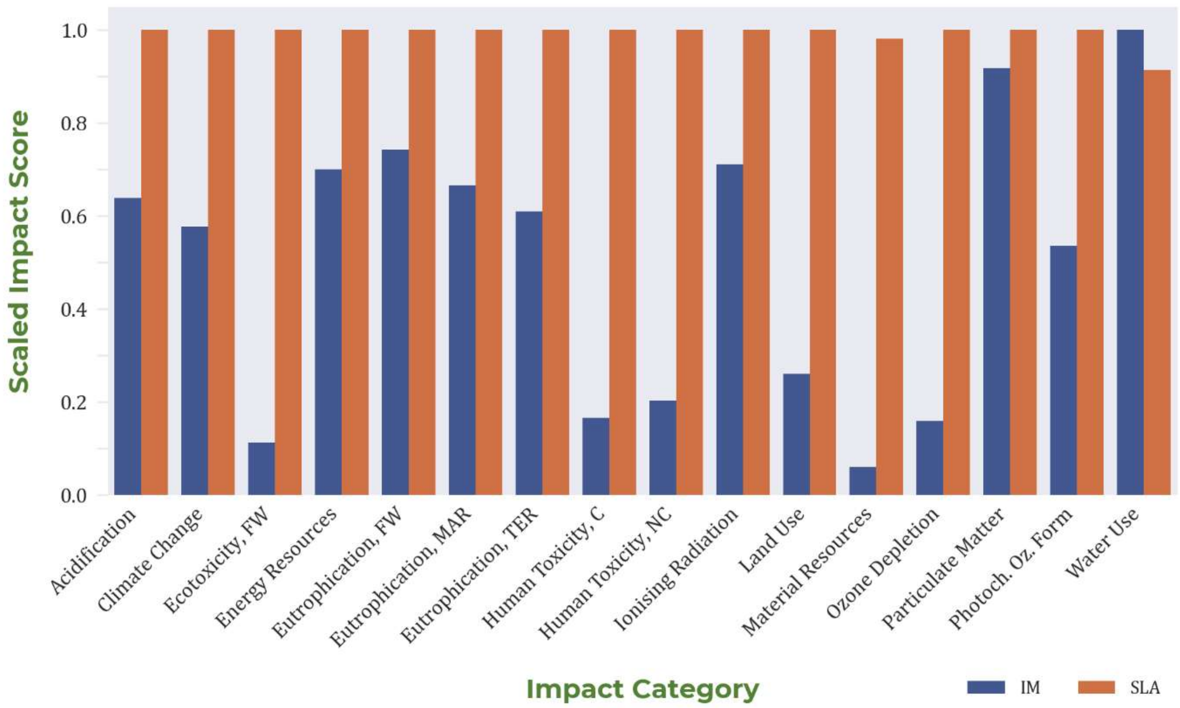

Figure 8: Characterised indicator results of injection moulding and storage of spare parts and the on-demand SLA printing in 2025, scaled relative to the largest, using the EF3.1 impact assessment family.

Normalised Results

Figure 10 presents the normalised indicator results for 2025, using the EF3.1 normalisation factors, indicating which impacts are of particular concern. While normalisation results are highly sensitive to the factors used (Prado et al., 2020), they aid in understanding the potentially critical impact categories for a product system and indicate which ones might particularly influence the aggregated weighting results. An evaluation of the possible biases introduced by normalisation indicates that categories such as toxicity and ionising radiation, which commonly dominating normalisation results due to data gaps, in this case do not significantly impact these outcomes, with the exception of freshwater ecotoxicity for SLA (for more detailed results refer to Appendix Z, File VIII and discussion of influence on results see Section 6.3.2). It shows that for SLA material resource use, freshwater ecotoxicity, energy resource use, and freshwater eutrophication are the most critical, followed by climate change and non-carcinogenic human toxicity. For IM, the most concerning impacts are energy resource use, freshwater eutrophication, and climate change.

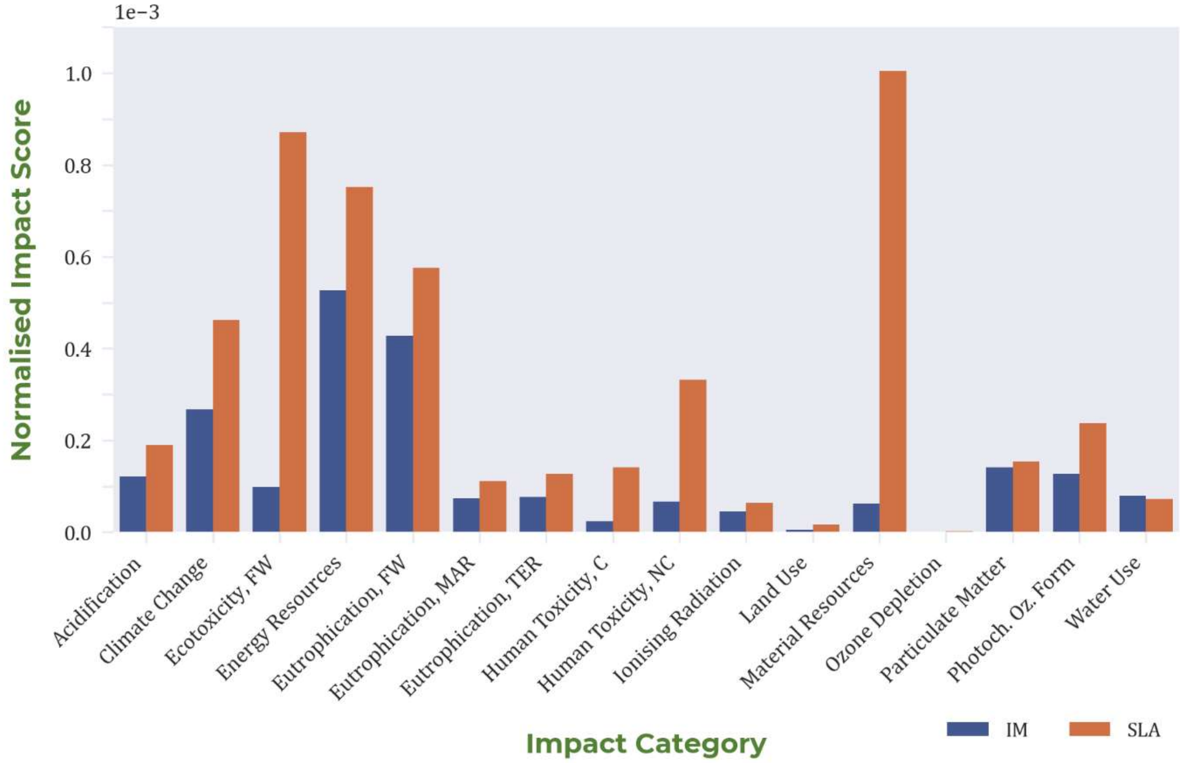

Figure 9: Normalised indicator results of injection moulding and storage of spare parts and the on-demand SLA printing in 2025, using the EF3.1 impact assessment family.

5.1.2. Weighed Impacts in 2050

Figure 10 illustrates the weighted outcomes for both 2025 and future projections. As mentioned in the methods Section 2.2.1 and discussed in limitations Section 6.3.2 the weighted results highly depend on the normalisation factors used (in this case, from EF3.1). The weighing contribution evaluation (see Appendix Z, File VIII) indicates that, for IM, climate change impacts and energy resource use primarily dominate the weighted results. For SLA, in addition to these two impact categories, material resource use also makes a significant contributions. Therefore, conclusions drawn from these results should be approached with caution, as relative performance may vary with different normalisation and weighing methods.

The results indicate that in 2025, the weighted impact of the SLA printed pump enclosure is nearly double that of the IM alternative. By 2050, enhancements in the background system alone (Base) cut IM's impact by 20%, whereas SLA experiences a 25% reduction compared to its 2025 Base impacts. In the realistic scenario, the impacts decrease by 39% for IM and 49% for SLA by 2050, relative to their 2025 performance. In the ambitious scenario, IM achieves a 53% reduction, and SLA achieves a 64% reduction. Only in the case that SLA undergoes significant technological development (SLA 2050 Ambitious), while IM's development stagnates and only the background system changes (IM 2050 Base), SLA does achieve a slightly lower overall footprint than IM. However, when technology improvements are applied to both options, IM maintains a notable advantage, demonstrating approximately 37% to 48% lower weighted impact compared to SLA in the same improvement scenario (e.g., IM Realistic versus SLA Realistic).

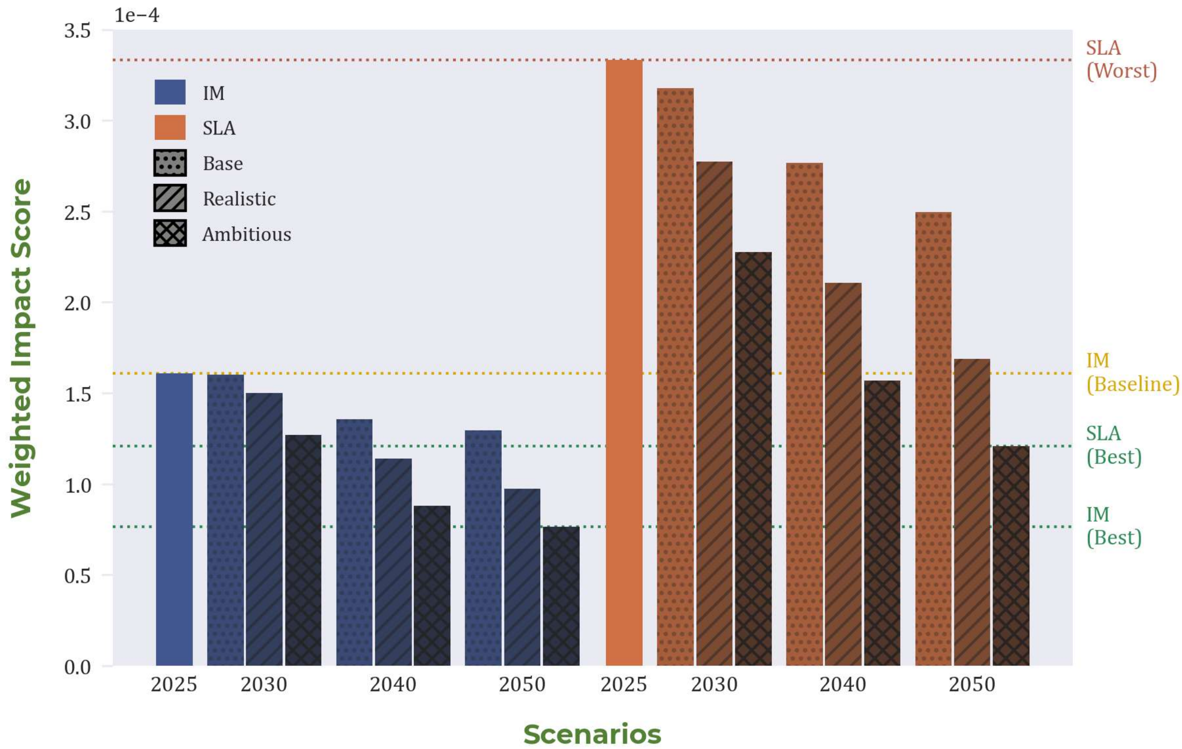

Figure 10: Weighed results of injection moulding and storage of spare parts and on-demand SLA printing in 2025, based on the normalised results using the EF3.1 factors. Future projections (2030, 2040, & 2050) based on the IMAGE SSP2 RCP2.6 scenario (Base) and additional foreground changes (Realistic & Ambitious). The IM impacts in 2025 are seen as the baseline, against which the scenarios are compared.

5.2. Environmental Hotspot Identification

5.2.1. Lifecycle Stage Impact Contributions

To identify the lifecycle stages that contribute most significantly to the overall impacts, the characterised results were disaggregated by the lifecycle stage. The unit process impacts were aggregated into five stages: capital goods, material production, manufacturing, transport/storage/overproduction, and EoL treatment. The use phase has no impacts since there are no assumed emissions associated with using the housing. Disaggregation by stages was achieved by calculating the impacts for each unit process and then subtracting the impacts of the preceding stages (e.g. $Stage\ Impact_{Printing} = Impact_{\ Printed\ Part} - Impact_{\ Resin} - Impact_{\ Printer}$). Which processes are attributed to which stage can be seen in Appendix C, Figure 1, while the calculation steps can be found in Appendix Z, File V. The results were examined for balance to verify that the total impacts of each stage match those of the entire system.

In Figure 11, the weighted impacts of each stage for both alternatives in 2025 and SLA 2050 Ambitious are illustrated. Both alternatives exhibit the large impacts in the raw material production (ABS/resin). For SLA, the largest contributor is the manufacturing stage, where the part is printed and post-processed; in contrast, the impacts for IM at this stage are relatively low. For IM, the second and third largest contributing stages are storage and overproduction, followed by manufacturing, EoL treatment, and transport. Also, equipment and tolling barely contribute to the overall impacts. In the 2025 Ambitious scenario, the impacts of SLA significantly decrease compared to their 2025 Base values in manufacturing (70%), equipment and tooling (70%), and material production (60%). In comparison to the total 2025 Base impact, this results in decreases of 30%, 19%, and 15%, respectively. For transport and EoL reductions are less than 1% of the total 2025 Base impact.

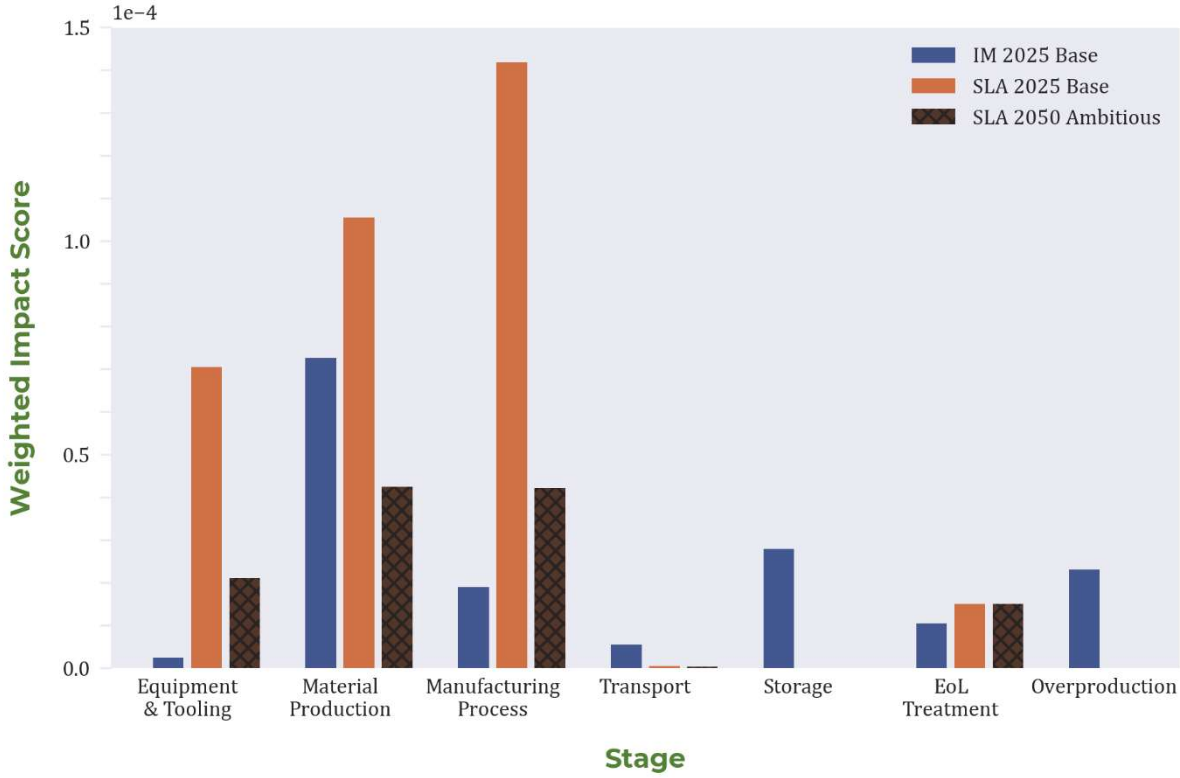

Figure 11: Weighed life cycle stage contributions for injection moulding and SLA printing in 2025. For IM, equipment and tooling include the transported machine and mould; material production of the transported ABS; manufacturing the energy use and other inputs during injection moulding; transport storage, and EoL treatment include the corresponding processes. For overproduction, all impacts of the unused parts (incl. production and EoL) are attributed to it and not included in the other stages. For SLA, only the printing and post-processing have been grouped into the manufacturing process.

5.2.2. Unit Process Contributions

For a more detailed assessment, contributions have also been calculated at the unit process level for 2025 and are shown in Tables 6 and Table 7.

Table 6: Relative contribution of the lifecycle stages of the injection moulded chassis in the 2025 Base scenario.

	Stages - IM 2025 Base								
Impact category	**Machin.**	**Mould**	**ABS Mix**	**Inj. Mould.**	**Transport**	**Storage**	**Use**	**EoL**	**Overprod.**
Acidification	0%	1%	47%	15%	4%	15%	0%	2%	16%
Climate Change	0%	1%	46%	8%	3%	16%	0%	15%	12%
Ecotoxicity, FW	1%	1%	42%	10%	2%	18%	0%	12%	13%
Energy Resources	0%	0%	55%	11%	3%	14%	0%	1%	16%
Eutrophication, FW	0%	1%	8%	31%	1%	41%	0%	2%	16%
Eutrophication, MAR	1%	1%	40%	10%	8%	17%	0%	13%	12%
Eutrophication, TER	1%	1%	41%	7%	9%	23%	0%	4%	15%
Human Toxicity, C	2%	4%	40%	10%	4%	19%	0%	7%	14%
Human Toxicity, NC	4%	3%	14%	23%	7%	24%	0%	14%	12%
Human Health	0%	0%	1%	54%	1%	26%	0%	0%	17%
Land Use	1%	2%	8%	8%	18%	45%	0%	3%	15%
Material Resources	11%	2%	17%	10%	5%	36%	0%	3%	16%
Ozone Depletion	1%	1%	13%	26%	8%	34%	0%	2%	15%
Particulate Matter	1%	1%	56%	4%	7%	13%	0%	1%	16%
Photoch. Oz. Form	0%	1%	50%	9%	8%	13%	0%	3%	15%
Water Use	0%	1%	55%	19%	0%	6%	0%	2%	16%
Average	1%	1%	33%	16%	5%	22%	0%	5%	15%

Table 7: Relative contribution of the lifecycle stages of the SLA printed chassis for the 2025 Base scenario.

	Stages - SLA 2025 Base						
Impact category	**Printer**	**Resin**	**Printing**	**Treament**	**Transport**	**Use**	**EoL**
Acidification	22%	36%	27%	14%	0%	0%	1%
Climate Change	9%	27%	32%	18%	0%	0%	14%
Ecotoxicity, FW	8%	80%	5%	5%	0%	0%	2%
Energy Resources	8%	37%	35%	20%	0%	0%	0%
Eutrophication, FW	24%	30%	36%	10%	0%	0%	0%
Eutrophication, MAR	18%	37%	30%	12%	0%	0%	3%
Eutrophication, TER	18%	36%	32%	12%	0%	0%	3%
Human Toxicity, C	13%	68%	12%	6%	0%	0%	2%
Human Toxicity, NC	30%	24%	34%	9%	0%	0%	3%
Human Health	8%	30%	54%	9%	0%	0%	0%
Land Use	11%	28%	52%	7%	0%	0%	0%
Material Resources	52%	19%	23%	6%	0%	0%	0%
Ozone Depletion	6%	36%	41%	16%	0%	0%	0%
Particulate Matter	25%	42%	17%	14%	0%	0%	1%
Photoch. Oz. Form	13%	39%	23%	22%	0%	0%	2%
Water Use	12%	33%	41%	11%	0%	0%	4%
Average	17%	37%	31%	12%	0%	0%	2%

The results of the unit process contributions provide more granular insights for IM and SLA. We observe that the largest contributions, next to raw materials, stem from the storage stage, followed by overproduction and IM itself, while transport, machine, and mould contribute relatively little. Using the Sankey diagram contributions in the Activity Browser, it is evident that the storage impacts are primarily driven by the electricity consumption of the warehouse and the building itself, which are dependent on the overall storage period.

For SLA, the table provides insight into the breakdown of manufacturing impact contributions between printing and post-processing. It shows that, after the raw material, printing contributes the most across the categories, followed by the printer and treatment, while transport and EoL contribute relatively little. The Sankey contribution analysis showed that for the SLA treatment, the largest contribution comes from the use and disposal of solvents during the washing process.

The unit process contributions of SLA have also been calculated for 2050, revealing that the relative contribution of printing decreases notably under future conditions, while resin, treatment, and EoL experience relatively increased contributions. However, these changes do not necessarily indicate an absolute reduction in the corresponding stage, but rather a shift in contributions. Detailed results are presented in Appendix C, Tables 1 and 2.

Table 8 summarises the stages that contribute the most to the impact categories with the highest normalisation results. Normalization showed that for SLA, the impacts are especially significant in material resource consumption and freshwater ecotoxicity. The contribution tables show that the former is primarily attributed to the substantial resources required for printer manufacturing, while the latter is primarily influenced by the resin's composition.

Table 8: Overview of stages contributing to impacts in key categories with the highest normalised results by ≥10%. IM machine, mould, and transport and SLA transport have been omitted due to their low contributions in these key categories.

	Impact driver	Influenced key impact categories
Injection moulding	ABS mix	High contribution to energy use (55%) and climate change (46%).
	Injection moulding	Moderate for freshwater eutrophication (31%) and energy use (11%); low for climate change (8%).
	Storage	High for freshwater eutrophication (41%); moderate for climate change (16%) and energy use (14%).
	Overproduction	Moderate contributions across energy use (16%), freshwater eutrophication (16%), and climate change (12%).
	EoL treatment	Moderate contribution to climate change (15%).
SLA printing	Printer	High for material use (52%); moderate for non-carcinogenic toxicity (30%) and freshwater eutrophication (24%).
	Resin	High for ecotoxicity (80%); moderate for energy use, freshwater eutrophication, climate change, toxicity, and material use (20–37%).
	Printing	Moderate contributions for freshwater eutrophication, energy use, toxicity, climate change (32–36%), and material use (23%).
	Post-processing	Moderate for energy use (20%) and climate change (18%); low for freshwater eutrophication (10%).
	EoL treatment	Moderate contribution to climate change (14%).

5.3. Sensitivity Analysis

5.3.1. Effect of Scenario Parameters

Modelling Approach for Parameter Sensitivity

To evaluate the overall sensitivity of the model, the influence of individual scenario parameters within the Ambitious scenario on the projected results for 2050 was examined. This analysis was conducted by modifying the scenario difference file (see Appendix Z, File VI) for Activity Browser, whereby each parameter change (e.g., printer lifetime extension, resin impact reduction) was introduced one at a time. The steps were as follows:

1. **Step: Run Impact Assessments for Baseline and Improved Scenarios**
   a. 2025 Base Scenario: reference impact against which reductions are compared
   b. 2050 Base Scenario: future reductions only background
   c. 2050 Ambitious Single Parameters: For each parameter (e.g., printer lifetime), an impact assessment is conducted with only this improvement implemented.
2. **Step: Calculate the absolute impact reduction through each parameter**
   a. For given parameter i, reductions are calculated as follows:

$$\Delta i = Impact_{2050\ Base} - Impact_{2050\ Ambitious\ (i)}$$

3. **Step: Calculate percentage reduction per impact category**
   a. Divide the absolute reduction by impact of the 2025 Base Scenario:

$$\%\ Reduction_i = \left(\frac{\Delta i}{Impact_{2025\ Base}}\right) \times 100$$

4. **Step: Normalise and aggregate to overall percentage reductions**
   a. Normalise, weight, and sum impact reductions through future background and individual parameter foreground changes.

Sensitivity to IM Scenario Parameters

The weighted results of the sensitivity analysis for IM are presented in Figure 12. The findings indicate that the share of recycled inputs is the most influential parameter, offering the greatest opportunity for reducing environmental impacts, with a 27% reduction by 2050 by increasing the share of recycled inputs from 0% to 50%. This is followed by the reductions from the background changes of about 20%. Transitioning transportation from lorry to rail also results in a noteworthy decrease in impacts of 8% (i.e. shifting from 0% to 50% rail). While enhancing IM machine efficiency and reducing overproduction are beneficial, their influence on the reductions is minimal, offering only minor improvements of around 0.5% to 1%, despite substantial parameter changes (i.e. 30% reduction in machine energy use, decreasing from 20% to 5% overproduction). Increasing recycling rates from 15% to 60% at the EoL yields mixed results across various impact categories, resulting in a slight overall increase in impacts of 0.02%. This can be explained through the emissions generated during the recycling process, which are attributed to this product system. While implementing recycling increases the impacts due to the cut-off by the classification approach (resulting in the subsequent use of the recycled granulate being burden-free), IM ultimately benefits from this modelling approach, as the recycling inputs significantly reduce the overall impacts of the system. A theoretical evaluation was conducted in Section 5.3.4 to assess the influence of recycling modelling on SLA.

It is important to note that there is a discrepancy between the sum of the individual parameter reductions and the overall reduction attained when all parameters are applied concurrently, as in the Ambitious 2050 scenario. The summed reductions are approximately 3.5% lower than the total reduction achieved by implementing the Ambitious 2050 scenario. This discrepancy may stem from interactions and synergistic effects among the parameters that are not entirely captured when assessing them in isolation.

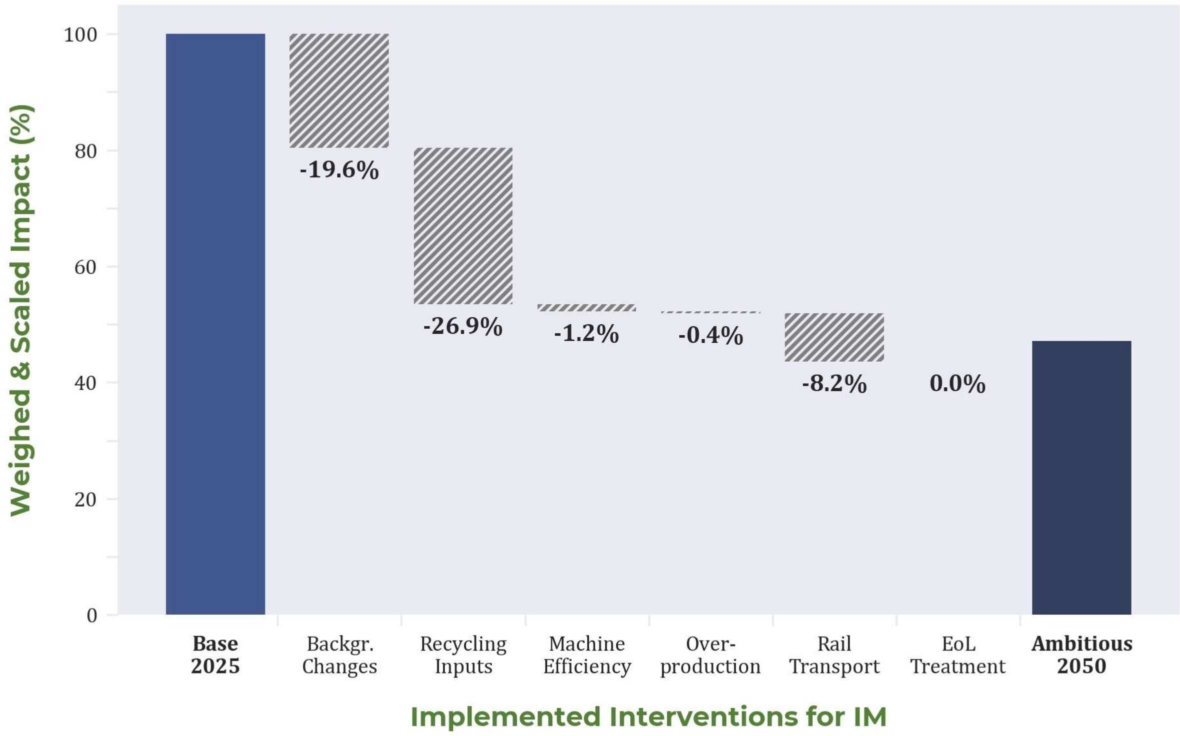

Figure 12: Results of the scenario parameter sensitivity analysis for the IM Ambitious scenario. Impact reductions have been normalized, weighted, and scaled relative to the largest. Hashed bars and percentages indicate how each implemented intervention reduces impacts compared to the SLA 2025 Base scenario. The discrepancy between the sum of individual parameter reductions and the actual reduction in the full scenario implementation is either due to reciprocity effects or unforeseen modelling influences.

In Table 9, the influence of implementing each parameter on the top impact categories (based on normalisation) for IM is shown (for full table see Appendix E, Table 1). Background changes significantly reduce freshwater impacts, while using recycling inputs achieves high reductions across almost all impact categories. With multiple parameters, we can observe a slight shift in burden, where a reduction in one category (such as climate change for EoL treatment) is accompanied by increases in others.

Table 9: Relative impact reductions through implementation of ambitious parameters for 2050 in relation to the IM 2025 Base scenario. Shown for selected impact categories based on values with high normalised results. The discrepancy between the sum of individual parameter reductions and the actual reduction in the full scenario implementation is either due to reciprocity effects or unforeseen modelling influences.

	Relative Parameter Reductions, IM					
Impact category	Background	Recycling Inputs	Machine Efficiency	Overpro-duction	Rail Transport	EoL Treatment
Acidification	-22.4%	-27.5%	-1.2%	-1.2%	-7.8%	0.7%
Climate Change	-20.2%	-27.1%	-0.5%	1.2%	-7.7%	-1.7%
Energy Resources	-13.5%	-32.9%	-1.5%	-1.0%	-9.6%	0.9%
Eutrophication, FW	-79.1%	-4.1%	-2.3%	-0.3%	-2.2%	0.5%
Particulate Matter	3.1%	-34.1%	-0.5%	-1.7%	-12.1%	0.7%
Photoch. Oz. Form	-16.4%	-29.0%	-0.7%	-1.0%	-8.3%	0.8%

Sensitivity to SLA Scenario Parameters

To derive the sensitivity results for SLA, the same methodology used for IM was employed, and the results are shown in Figure 13. The analysis reveals that for SLA, the model is particularly sensitive to resin-related impact reductions, achieving the largest overall reductions of 13%, by reducing the resin impact by 50%. However, the modelled impact reduction, represented solely by a 30% decrease in resin input (using 0.7 kg of resin instead of 1 kg for printing), does not take into consideration the possibility of environmental burden shifting to other impact categories due to the use of different feedstocks and chemicals. Second largest reductions of around 11% are achieved by extending the printer lifespan, by tripling its lifetime. This is followed by the energy efficiency improvements of the printer, yielding a 8% impact reduction through a 60% reduction of energy consumption per part. This is followed by a 6% impact reduction through reducing solvent use by 50%. Improving curing efficiency and shifting transport to rail achieved only marginal reductions of less than 0.5%. While the printing time and thus its energy consumption per pump were only roughly estimated (influencing the baseline energy consumptions based on which the improvements are modelled), as the influence is so low, the uncertainty in the estimate is likely not significantly influencing the results. The changes in the background system alone contribute 26% to the reduction in overall impacts, highlighting the importance of considering the influence of societal transitions when evaluating improvements in emerging technologies.

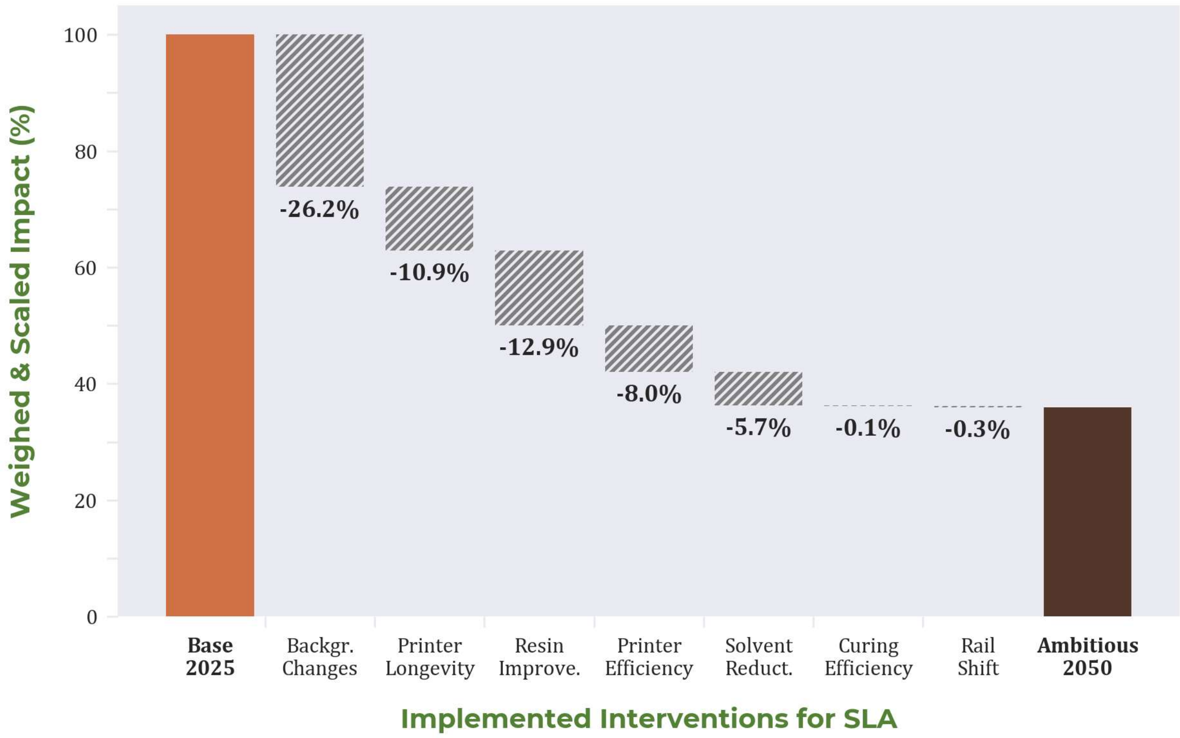

Figure 13: Results of the scenario parameter sensitivity analysis for the SLA Ambitious scenario. Impact reductions have been normalized, weighted, and scaled relative to the largest. Hashed bars and percentages indicate how each implemented intervention reduces impacts compared to the SLA 2025 Base scenario.

A more detailed breakdown by impact category (see Table 10) identifies which interventions are most effective at reducing the impacts in the key categories where SLA experienced the highest normalised impacts (for full Table, see Appendix E, Table 2). The key factors for reducing freshwater ecotoxicity and material resource use are the reduction of resin impact and the extension of printer lifetime, respectively. Background changes result in significant reductions in freshwater eutrophication, climate change, and energy resource use.

Table 10: Relative impact reductions through implementation of ambitious parameters for 2050 in relation to the SLA 2025 Base scenario. Shown for selected impact categories based on values with high normalised results.

	Relative Parameter Reductions, SLA						
Impact category	Background	Printer Lifetime	Resin Impact	Printer Efficiency	Solvent Reduction	Curing Efficiency	Rail Transport
Climate Change	-41.7%	-3.2%	-9.0%	-3.1%	-7.1%	0.0%	-0.2%
Ecotoxicity, FW	-3.3%	-4.6%	-39.0%	-2.4%	-2.3%	0.0%	0.0%
Energy Resources	-32.2%	-3.3%	-15.0%	-8.3%	-8.5%	-0.1%	-0.2%
Eutrophication, FW	-52.6%	-11.9%	-5.8%	-6.7%	-2.8%	-0.1%	0.0%
Human Toxicity, NC	-11.6%	-18.6%	-10.7%	-16.0%	-2.9%	-0.2%	-0.5%
Material Resources	1.9%	-34.1%	-9.9%	-13.9%	-2.2%	-0.2%	-0.2%

5.3.2. Effect of Production Scale

The main impact assessment assumes a large-scale production run of 50,000 parts for the IM spare part, as this is deemed a reasonable scale for a commonly failing part such as the pump produced during the initial production run. However, several researchers pointed out that AM can be more competitive than IM in small-scale production runs from both operational (Cardeal et al., 2022; Gao et al., 2015; Tofail et al., 2018) and environmental perspectives (Jung et al., 2023; Kokare et al., 2023). To evaluate whether there is a production volume crossover where SLA, with its constant per-part impact, might become environmentally preferable, scenarios with small-scale production runs were examined.

Modelling Approach for Production Scales

To implement the different production scales, the per-part mould attribution was adjusted. As this scenario follows a more on-demand manufacturing approach, storage and overproduction were also adjusted. The storage time and overproduction values for IM were modified, as it is assumed that with a smaller-scale production run, parts would be produced in time, allowing for less than 10 years of storage, which enables better demand prediction. It is assumed that with a low production scale, the parts would only be stored for 2 years instead of 10, while overproduction is reduced from 20% to 5%. An additional parameter to consider is the mould material. While a Class 103 mould with higher-quality steel might be used for a large-scale production run (25,000-100,000 parts), a Class 105 mould using cast metals such as aluminium or epoxy would be used for small runs (<500 parts), as these are more economical (Ye, 2023). A preliminary assessment showed that a cast aluminium mould has lower environmental impacts than a low-alloyed steel mould. An additional option, incorporating a 3D-printed core (SLA with epoxy resin) and an aluminium enclosure, as suggested by Formlabs (2022) for small-scale rapid tooling, it was modelled but demonstrated similar impacts to the full cast aluminium option. Thus, cast aluminium and low-alloyed steel are used to model lower and upper bounds for mould impacts. The scenario parameters are summarised in Table 11, with a detailed SDF implementation provided in Appendix Z, File VI. The reference year for this assessment is 2025, and results are compared against the SLA 2025 base scenario.

Table 11: Scenario parameters for modelling the effect of different production scales of IM.

Scenarios	Production Run	Storage Time	Over-production	Mould Material
IM 2025 Base	50,000 parts	10 years	20%	Steel, low alloyed
IM 2025 Low Vol. Steel	50-500 parts	2 years	5%	Steel, low alloyed
IM 2025 Low Vol. Aluminium	50-500 parts	2 years	5%	Aluminium, cast alloy

Impacts of Different Production Scales

As shown in Figure 15, the results indicate that the impacts of IM differ significantly at low production volumes, ranging from 50 to 500 parts. A crossover occurs around 250-350 parts, where the environmental impacts of SLA and IM are in a similar range, while for runs below 250 parts, SLA exhibits notably lower environmental impacts. At 50 parts, the weighted impact of IM per part is approximately four times higher than that of SLA. The choice of mould material has a considerable influence on the impact at low production runs, but this diminishes at production scales above 500 parts.

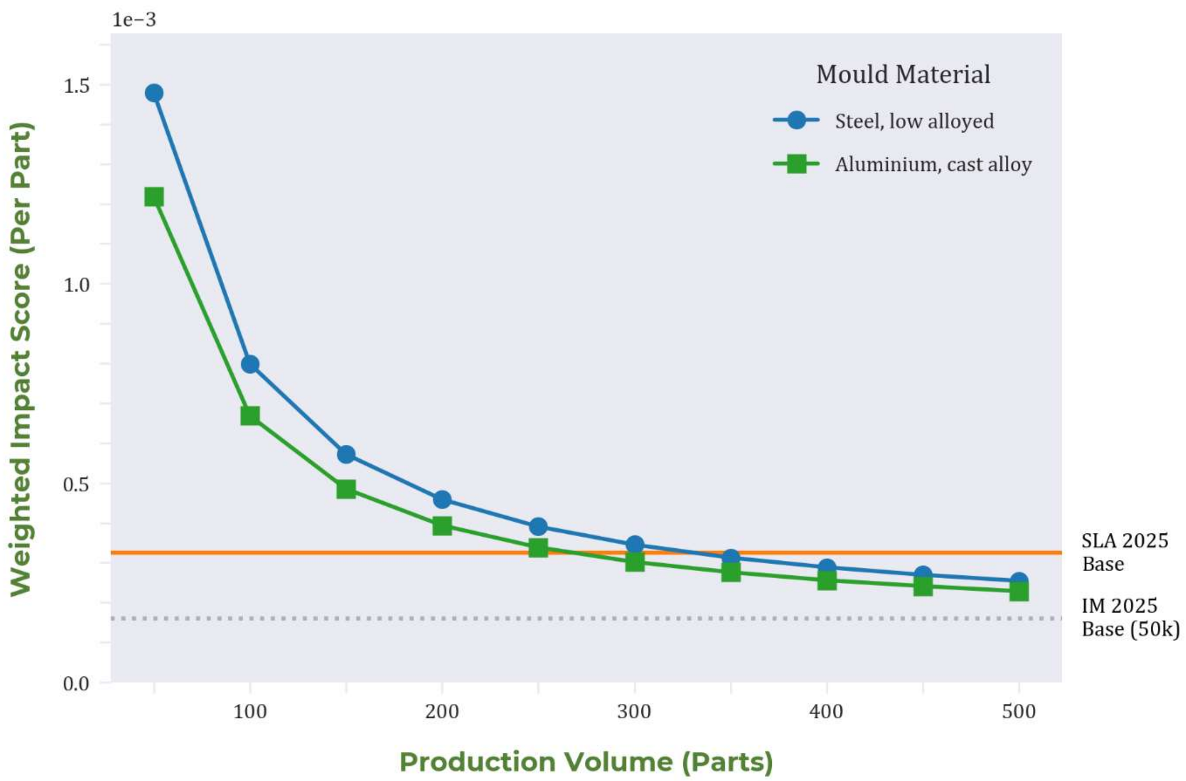

Figure 14: Weighed LCIA results comparing different production scales and mould materials for IM against the per part impact using SLA.

5.3.3. Effect of Storage Duration

In the main IM scenarios, a fixed 10-year storage duration, aligned with the EU spare part availability requirements, is assumed, along with a 20% overproduction rate in the Base scenarios. However, in practice, storage duration varies based on the actual demand for spare parts over time, and different availability periods are required for different types of products. Therefore, this section examines how varying storage durations, ranging from a minimum of 2 years (aligned with the EU minimum warranty for white goods) to a maximum of 20 years, affect the environmental impacts of the IM part compared against SLA.

Modelling Approach for Storage Duration

The scenarios are modelled by varying the storage durations and adjusting the overproduction. The overproduction is expected to change, as a shorter storage duration is anticipated to lead to more accurate demand predictions, thereby reducing overproduction, while longer storage periods are expected to increase it. Different storage durations are modelled for both 2025 and 2050 reference years, and the remaining foreground changes are included for the 2050 base scenario. Overproduction is projected to vary from 5% for 2-year storage to 40% for 20-year storage. The results are compared against the IM 2025 & 2050 Base scenarios (10 years of storage, 20% overproduction) and the IM 2050 Ambitious scenario (10 years of storage, 5% overproduction). Parameter changes are shown in Table 12, and a detailed SDF implementation is provided in Appendix Z, File VI.

Table 12: Scenario parameters for modelling the effect of different storage durations of IM.

Scenarios	Parameters	Values				
IM 2025/2050 Base	Storage Time	10 years				
	Overproduction	20%				
IM 2050 Ambitious	Storage Time	10 years				
	Overproduction	5%				
IM + Varying Storage	Storage Time	2 years	5 years	10 years	15 years	20 years
	Overproduction	5%	10%	20%	30%	40%

Impact of Different Storage Durations

The assessment shows that, under 2025 conditions, even with 20-year extended storage, the impacts of IM are lower than those of the SLA printed part (see Figure 16). In the IM 2050 Base scenarios, the impact per part of IM surpasses that of SLA (Ambitious) when storage durations exceed 7.5 years. If IM undergoes ambitious improvements, its footprint will be smaller than that of SLA for storage durations of less than 20 years; only at that point does SLA become competitive. This indicates that, under current conditions, IM remains more favourable; however, for storage durations exceeding 10 years, SLA could become competitive or even preferable in the future.

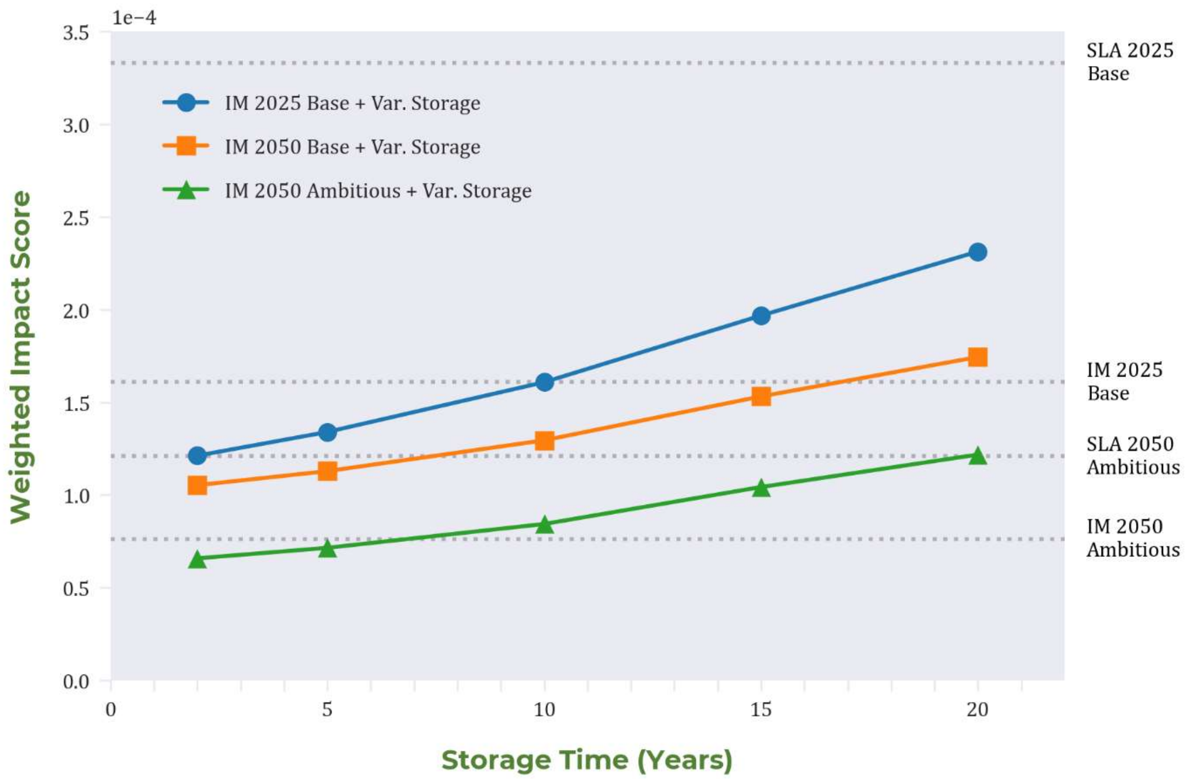

Figure 15: Weighed LCIA results comparing impacts of different storage durations for IM against SLA.

5.3.4. Effect of Recycling

In the main scenarios, the largest reduction in impact for the IM was achieved through increased recycling rather than actual technological improvements to the IM technology itself. These benefits are largely attributed to the chosen allocation approach for recycling impacts. In contrast, no recycling was assumed for SLA due to challenges associated with it being a thermoset plastic. The evaluation of whether using the same recycling assumptions could help SLA achieve similar significant impact reductions was not included in the main scenarios, as it is currently unavailable on a larger scale for fully recycling SLA printed parts. Voet et al. (2021) found successful experiments capable of recycling SLA printed parts; however, these often involved material property degradation or downcycling.

Modelling Approach for Recycling Scenarios

Due to the high uncertainty regarding the environmental impacts of large-scale recycling of photopolymer resin, the assessment simplifies its assumptions by applying the same recycling modelling for SLA as for recycled ABS. The transport distance for the recycled resin is also assumed to be 1500 km, similar to the transport distance of ABS granulate to Romania, reflecting the likely lower density of facilities capable of resin recycling compared to those for more common plastics. In the primary scenarios for IM recycling, inputs and outputs are assumed to differ, with EoL recycling rates being higher to compensate for losses and rising plastic demand. In these scenarios, however, recycling shares are modelled to be the same for both inputs and outputs at levels of 0%, 25%, 50%, and 75% recycling. The remaining percentage is assumed to be incinerated. The reference year for the modelling is 2025 using the Base scenarios. Parameter values are shown in Table 13, with a detailed SDF implementation provided in Appendix Z, File VI.

Table 13: Scenario parameters for modelling the effect of different recycling shares of IM and SLA.

Parameters	Values			
Virgin Inputs	100%	75%	50%	25%
Recycling Share (Inputs & Outputs)	0%	25%	50%	75%
EoL Incineration	100%	75%	50%	25%

Impact of Different Recycling Shares

The environmental impacts of both IM and SLA decrease at similar rates as recycling shares increase (see Figure 17). Even with a 75% recycling share, SLA still demonstrates a higher environmental impact than IM under the 2025 Base scenario. The impact reductions achieved for SLA are comparable to the reductions modelled for SLA through resin impact reductions, as they both effectively model substitution of input material through quasi-burden-free materials. Recycling alone does not eliminate the impact difference between SLA and IM, as the reductions are on a scale similar to the resin efficiency improvements modelled for different time steps in IM.

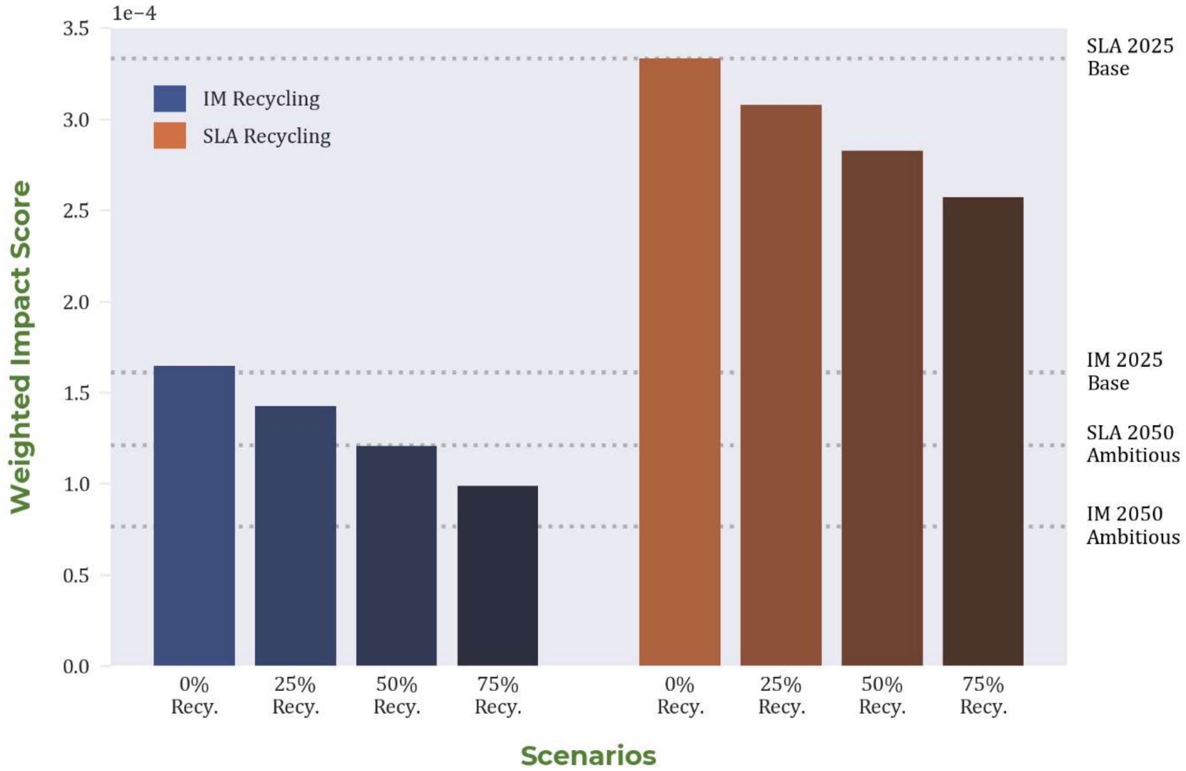

Figure 16: Weighed LCIA results comparing impact reductions of different recycling shares for both IM and SLA.

5.4. Consistency & Completeness Evaluation

5.4.1. Consistency Check

A consistency check was conducted to verify that data sources, assumptions, methods, and models were uniformly applied across both alternatives and aligned with the defined goals and scope. Overall, the consistency evaluation indicates that, while most elements are aligned, discrepancies in data age and technology coverage, primarily related to the used IM machine and SLA printer, as well as the estimated energy consumption, may affect their comparability. The modelling of both alternatives was approached similarly, and cut-offs, such as for factory buildings and packaging materials, were applied consistently. The detailed consistency assessment results and suggestions for improving consistency in future research are explained in Appendix D.

5.4.2. Completeness Check

Since no technical expert was available to directly assess the systems, the completeness evaluation relied on comparisons with existing literature. It was concluded that the modelling is consistent with previous literature, while extending it in key points regarding resin formulation, storage, and the impacts of overproduction. The relative environmental performance, where SLA has a greater impact than IM, aligns with the findings of previous studies. However, the relative difference between the two varies per study, likely due to differing assumptions about production scale or system boundaries. Full completeness check results and a more comprehensive discussion of results compared to previous literature are reported in Appendix.

6. Discussion

This study aimed to evaluate the environmental effects of long-term spare part supply, comparing IM and storage with on-demand SLA printing under both present and future scenarios, to determine which option is more environmentally sustainable. First, a suitable spare part, specifically a plastic WM pump housing, was selected. Second, various scenarios were established. Third, a pLCA was conducted, uncovering several insights and environmental trade-offs that must be considered when creating a sustainable long-term spare part strategy, which will be discussed in the following sections.

The discussion aims to contextualise the main findings (Section 6.1), discuss implications for different stakeholders (Section 6.2), reflect on the limitations and robustness of the insights (Section 6.3), highlight future research directions (Section 6.4), and summarising the contributions to the field (Section 6.5).

6.1. Contextualising the Findings

6.1.1. Operational Implications

IM is the more sustainable option for high-volume spare part production

The impact assessment indicates that in high-volume spare part production, the environmental impact of SLA printed pump housings is consistently greater across nearly all impact categories, nearly double that of IM in its current state in 2025. IM retains this advantage even in future scenarios, unless SLA improves significantly while IM stagnates. These findings support the argument that economies of scale give a substantial benefit to IM. This aligns with the results presented by Shi & Faludi (2020), who found that when fully utilised, SLA printing had roughly four times the environmental impact of an injection-moulded ABS part. The advantages of IM arise from its high throughput, lower per-part mould allocation at high volumes, and lower material impacts compared to SLA resin, along with its recyclability potential.

SLA printing outperforms IM in small-scale production

In the main scenario, a large production run of 50,000 parts was assumed, including both the parts for the product going to market and its spare parts, seeming representative of frequently failing components in consumer products. However, the sensitivity analysis on the production scale indicated that the relative performance can vary significantly, revealing that SLA has a particular environmental advantage in small-scale production. Specifically, a crossover in environmental impact occurs at a production scale of approximately 250-350 parts, where both technologies demonstrate similar effects, with SLA having about one-fourth of the impacts at 50 parts. This finding aligns with Telenko & Seepersad (2012), who identified a crossover at around 50-300 parts for selective laser sintering. It furthermore demonstrated that the choice of mould material influences the impacts, with cast aluminium moulds having lower impacts than those made of low-alloyed steel, but these differences become minor as the production scale increases. While selecting a different baseline assumption for production scale or utilising an alternative mould size estimate may influence the assessment outcomes, the sensitivity analysis revealed that for production scales exceeding 500 parts, the effects of the mould are considerably less critical in determining the overall impact. Overall, the findings confirm claims made in previous studies, which highlight the operational and environmental benefits of AM in small-scale production runs, providing a range at which this crossover can occur for IM and SLA (Cardeal et al., 2022; Gao et al., 2015; Jung et al., 2023; Kokare et al., 2023).

Storage duration does affect the environmental impacts of IM

The hypothesis that long-term storage of parts causes considerable environmental impacts was confirmed, as both storage and overproduction follow as the second and third biggest contributors after the material impacts. Spare part storage for over ten years results in substantial emissions from the warehouse building, its electricity, and heating consumption. The significant effect of overproduction stems from difficulties in accurately forecasting the demand for spare parts over extended storage periods, with researchers reporting ranges of 12% to 65% for various spare parts (Hemeimat et al., 2016; Kim et al., 2016). This is mainly because there is insufficient data on failure rates and historical time series when the initial production run, including the spare parts, is completed. The sensitivity assessment revealed that, based on current technological developments, even with storage periods extending up to 20 years, IM and storage have lower impacts. However, it indicated that under certain future conditions, a crossover could occur. If SLA makes significant advancements while IM development stagnates, by 2050, SLA-printed parts could compete with IM for storage durations of 8 years or more. Conversely, if IM also improves significantly, SLA would only be competitive for storage periods of approximately 20 years or longer. This suggests that, under current conditions, the storage duration is less important in determining whether SLA or IM is more sustainable, whereas under future conditions, the crossover shifts. The results from the contribution and sensitivity analyses indicate that, while assuming a fixed ten-year storage period simplifies the complex dynamics of spare part demand, factors such as material recycling and production scale have a greater impact on relative performance.

Decentralised production reduces transport impacts but provides limited overall benefits

A commonly noted benefit of AM is its potential to facilitate decentralised production, which helps minimise transport-related emissions (Cardeal et al., 2022; González-Varona et al., 2020; Kokare et al., 2023). This study confirms that decentralisation indeed leads to lower transportation impacts. Nevertheless, these savings are relatively minor when compared to the substantial environmental burdens associated with the printing process and material production. In this assessment, transportation contributes only a small fraction to the overall environmental impacts of both SLA and IM. While decentralised production reduces these transport emissions, the overall sustainability performance is influenced more heavily by factors such as material inputs, manufacturing energy usage, and equipment impacts. For IM, other logistical aspects, such as warehouse storage and overproduction, have a larger impact on the footprint of long-term spare part provision. Furthermore, in a European context, where transport by lorry or rail is relatively efficient, the advantages of decentralised production are evident yet limited. It is essential to note that if spare parts are to be transported intercontinentally or via air freight, the transport impacts may become more significant. Nonetheless, under the conditions modelled in this study, the benefits of decentralised production do not substantially alter the overall sustainability comparison between SLA and IM.

6.1.2. Technological Implications

Impact of printer energy consumption and importance of simultaneous grid improvements

The assessment revealed that, when considering future developments for SLA, substantial reductions of up to 64% can be achieved in the ambitious scenario, supporting the initial hypothesis that SLA, as a relatively new technology, has greater impact reduction potential than the more mature IM technology. It furthermore demonstrated that for SLA, the manufacturing process, including printing and treatment, has the highest impact of all stages, being approximately seven times that of IM. This is primarily driven by the high energy consumption per part. The stage contribution analysis suggests that improvements in the manufacturing phase, encompassing both printing and post-processing, could result in reductions of up to 30% by 2050. The reduction is notably higher than the 8% reduction shown for implementing improved printer efficiency in isolation, as in the sensitivity analysis. One plausible explanation is that background improvements, such as an enhanced and decarbonised electricity grid, substantially lower overall impacts in energy-intensive processes. This supports the hypothesis that background system enhancements can help an energy-intensive technology, such as SLA, become more competitive. The two key factors for reducing SLA's energy consumption are increasing print speed (to lower energy use per part) and reducing the baseline energy consumption during both active printing and idling phases. However, a potential trade-off exists: faster print speeds require more power, potentially offsetting any efficiency gains. As noted by Gutowski et al. (2017), such trade-offs can lead to efficiency plateaus similar to those observed in traditional manufacturing technologies. However, as Faludi et al. (2015) found that for the ProJet, energy consumption, even when idling, was comparatively high, it suggests that there are still efficiency gains to be made in the baseline energy consumption of SLA.

Improved resin formulations and recycling are essential for SLA's competitiveness
The significant environmental impacts of SLA printing are primarily driven not only by the energy-intensive printing process but also by resin production and the high per-part impact of the printer. This finding is consistent with Shi & Faludi (2020) work, which identified resin as the dominant contributor, followed by electricity use, waste, and printer manufacturing. In contrast, Mele et al. (2020) reported that the printer and its transportation were more significant, likely due to their focus on a desktop SLA printer characterised by lower utilisation, a shorter lifespan, different resin formulations, and assumptions involving air transportation. Despite uncertainties in resin composition data and limitations in matching ecoinvent processes, the recycling sensitivity analysis demonstrated that even substituting up to 75% of resin inputs with quasi-burden-free material, resulting in significant impact reductions, does not render SLA competitive with IM under current conditions. The substantial environmental burdens from the printing process and printer production continue to dominate the overall impacts, suggesting that even with improved material assumptions, other lifecycle stages would still maintain SLA's less favourable performance. When considering future conditions, significant changes occur. Background improvements and development of low-impact resin can further reduce the material production impacts. The stage contribution analysis indicates that these combined improvements could lead to an overall reduction of approximately 19% in SLA's impacts by 2050. This substantial future improvement supports recommendations from researchers (e.g. Cerdas et al., 2017; Kokare et al., 2023; Shi & Faludi, 2020) to focus not only on reducing energy consumption but also on developing more efficient, sustainable printing materials.

The Role of Printer Lifetime Extension in Lowering SLA's Environmental Burden
The analysis revealed that, after manufacturing and material production, the SLA printer's impact per part is the third-largest contributor in the base scenario. This high contribution is mainly attributable to the printer's short lifespan and slow printing process, which distributes the equipment manufacturing impacts over fewer parts. In contrast, the IM machine operates for 10 years with a throughput of approximately 16 kg of plastic per hour, whereas the SLA printer, with an estimated lifespan of only 5 years, produces merely two pumps in about 21 hours. Consequently, extending the SLA printer's lifetime would spread its environmental burdens over a greater number of parts, significantly reducing the per-part impact. The contribution analysis suggests that, when combined with background improvements, extending the printer's lifetime could reduce overall impacts by up to 15% by 2050. However, these benefits depend on maintaining a high utilisation rate throughout the extended lifespan. The trade-off lies in

diminishing returns when the printer is underutilised, as its impacts are less spread over a greater number of parts. Additionally, energy consumption during such idling times can significantly increase the per-part impact, as found by Shi & Faludi (2020). Moreover, a longer lifetime may necessitate maintenance, which could introduce additional impacts. However, the overall benefits of lifetime extension are likely to outweigh these drawbacks, provided maintenance is optimised. Overall, the findings underscore that lifetime extension is a crucial strategy for enhancing the sustainability of SLA printing. Nonetheless, it should be implemented alongside improvements in energy efficiency and resin formulations.

Material recycling drives the sustainability advantage of IM
The environmental footprint of IM is mainly dominated by the impacts of its raw material production (ABS), followed by storage, overproduction, and the manufacturing process itself. Material selection is thus critical, since the choice of plastic mainly determines the overall environmental performance of IM. Although ABS is often associated with higher environmental burdens, the results indicate that even when choosing a higher impact plastic, the impacts of IM remain lower than those of SLA under current conditions. The analysis showed that improvements, such as increased machine efficiency or reductions in overproduction, yield only modest improvements, whereas increasing recycled content can achieve larger reductions, as these inputs are mostly burden-free. This suggests that, regardless of other improvements, the high contribution of raw material impacts means that only significant increases in recycled inputs can further lower IM's overall footprint. As discussed earlier, while recycling does significantly benefit IM in reducing impacts, similar improvements have been included for SLA in the form of resin impact reductions.

6.1.3. Answering main RQ

These insights together answer the main research question: *"What long-term spare part provision strategy (on-demand SLA printing versus injection moulding and storage) provides the most sustainable solution for spare plastic housing components of washing machines?"* IM and storage, currently and in future scenarios, appear to be the more environmentally friendly strategy for supplying WM plastic housing spare parts in high volumes. At lower production volumes, SLA becomes competitive with IM or even has lower environmental impacts. If SLA undergoes significant improvements, reducing impacts of printing, resin, and printer manufacturing, it could make it competitive with IM even at larger scales.

6.2. Implications for Different Stakeholders

6.2.1. Implications for Product and Spare Part Manufacturers

When selecting a spare part strategy, manufacturers must consider the production scale of the part and its demand patterns. For high-volume production, IM benefits from economies of scale, achieving lower per-part impacts. In contrast, for low-volume, on-demand, or customised spare parts, AM via SLA can offer environmental advantages. It might also be beneficial to leverage hybrid strategies, utilising IM for bulk production and SLA for specialised, low-volume parts or to produce additional production runs if the initial demand prediction was inaccurate. Additionally, selecting the right material is crucial; evaluating low-impact plastics and incorporating recycled materials can further reduce environmental burdens for both IM and AM processes. Operational efficiency can be improved by enhancing demand forecasting for long-term predictions and optimising inventory management to minimise overproduction and mitigate storage impacts. Although decentralised production through AM can reduce transport emissions, these benefits do not outweigh the higher impacts of AM itself, as long as spare parts are transported using low-impact means of transportation, such as rail or truck, while avoiding transportation by airplane.

Finally, standardising product components that perform similar functions can reduce component diversity, thereby streamlining inventory management, as a smaller variety of parts needs to be kept in stock. With a lower part variety, the moulds can also be stored and used for additional production runs to meet spare part demand, thereby reducing storage requirements. Additionally, when considering AM for spare part production, product design needs to be adjusted to be compatible with both technologies, enabling on-demand production for spare part supply while leveraging the high-volume production benefits of IM for the initial production run.

6.2.2. Implications for AM Technology Developers

For AM technology developers, advancing material innovations, improving energy efficiency, and extending equipment lifespan are key. Research into recyclable, low-impact resin formulations is crucial, given that resin production is a major contributor to SLA's environmental impacts. Enhancing energy efficiency, particularly by reducing baseline energy consumption and optimising print speed, is also critical. It is crucial to ensure that higher print speed and greater power consumption do not counteract each other, in order to ultimately lower the per-part impact. Furthermore, extending the operational lifespan of SLA printers under high utilisation can significantly lower per-part equipment impacts, provided that maintenance is optimised to minimise additional burdens. Overall, technology developers should focus on integrating improvements across material, energy, and equipment performance to enhance the sustainability of AM processes.

6.2.3. Implications for Policymakers

Policymakers play a vital role in creating an enabling environment for sustainable spare part provision. Regulatory standards should emphasise not only the availability of spare parts but also low-impact production practices. In addition to incentivising the use of recycled content and the decarbonisation of the energy grid, policy efforts should focus on supporting manufacturers in selecting the appropriate technology for their specific spare part needs. Furthermore, incentivising the standardisation of components in consumer products, potentially even across brands, could streamline the current vast diversity of components that are product-specific yet serve the same functions, reducing storage requirements and overproduction. Moreover, targeted support for material innovations in AM is crucial. Funding initiatives and collaborative research projects can accelerate the development of low-impact, recyclable resin formulations and enhance recycling processes. Such material advancements will help lessen the environmental footprint of SLA printing, boosting its competitiveness in niche applications. Lastly, policies that promote the exploration of hybrid design strategies, where parts are designed to be manufacturable by both IM and AM, will provide manufacturers with the flexibility to optimise production based on volume, demand, and sustainability criteria.

6.3. Limitations

Several limitations regarding the data, modelling assumptions, modelling, and methodological choices may affect the assessment outcomes.

6.3.1. Data, Assumptions, & Modelling

In this study, data from an older SLA printer, alongside a more recent IM machine, are used, introducing discrepancies in temporal coverage and technology maturity that may affect the comparability of the two alternatives, particularly regarding their energy consumption. Although a more current SLA system might exhibit lower energy consumption per part, the high energy demands during printing are consistent with the literature. Additionally, the energy usage data for IM relies on ecoinvent estimates from 2007. This could overstate the energy consumption for IM, but given that the impacts of the manufacturing process are low compared to other stages like material production, it is expected not to change the impacts of IM significantly. For the SLA, actual measured energy consumption per time was used, as reported by Faludi et al. (2015). However, print times for SLA had to be estimated to match pump components, due to the absence of a CAD model and slicing software. This introduces uncertainty to the actual time and, consequently, the energy consumption per part. This may affect the absolute impact of the printing process, potentially shifting the balance between energy and resin contributions; however, the finding that SLA is more energy-intensive than IM is expected to hold for large-scale production, even if energy consumption is estimated more accurately.

Lifespan calculations for IM and SLA machinery rely on assumptions about operational hours and production outputs that may not accurately reflect real-world conditions. The model assumes continuous, high-utilisation operation (24 hours per day with 10% downtime). IM is modelled with a 10-year lifespan (producing about 81 pumps per hour), while the SLA printer is assumed to last 5 years (producing two pumps in 21 hours). Real-world factors, such as regional differences (e.g., holidays), maintenance practices, and the amount of time the machines spend idling, could affect these estimates. Although these assumptions might overstate or understate the impacts of equipment per part, especially for SLA, the advantage of IM due to its high throughput, significantly reducing per part equipment impact, particularly at high volumes, is expected to remain robust.

The **SLA resin composition** was approximated due to a lack of exact ecoinvent matches, and alternative, lower-impact resin formulations were not fully explored. Even when substituting up to 75% of resin inputs with quasi-burden-free material, per-part impacts of SLA remain higher than those of IM. While potential advancements in biobased resins and recycling processes could narrow this gap, the sensitivity analyses indicate that the difference between IM and SLA will persist unless dramatic improvements in resin impact with simultaneous recycling occur.

Similarly to SLA, the IM model proved to be particularly sensitive to changes in material inputs, specifically the **share of recycling**. The substantial reduction potential of increasing the recycling share is connected to the cut-off by classification approach, where the recyclate is considered burden-free. Alternative allocation methods and their impact on the results have not been explored. However, the recycling sensitivity analysis showed that, under current conditions, even with high recycling of SLA resin, its per-part impacts remain higher than those of IM. Additionally, since the only available plastic recycling data from ecoinvent at the time of the study stems from India, it may not accurately reflect European recycling conditions. Although these assumptions might understate EoL impacts of IM if actual treatment processes have higher burdens, its relatively low contribution indicates that results of EoL treatment are not expected to alter the overall results significantly.

The **mould dimensions** and material requirements were estimated using simplified calculations, which may not fully capture the complexity of mould design and thus could overstate or understate the mould impacts, particularly in low-volume production where mould impacts are more pronounced. However, the sensitivity analysis showed that variations in mould size have a diminishing effect at higher production volumes.

For the **spare part storage**, a fixed 10-year storage period was assumed to meet EU requirements, though real-world demand is dynamic. Extended storage increases overproduction and warehouse energy use, while shorter durations reduce these impacts. The sensitivity analysis indicates that, despite variability in storage duration, production scale and recycling remain the most critical drivers, with the impacts of IM remaining lower than those of SLA under current conditions, even with extended storage of up to 20 years.

6.3.2. Methodological Choices

In the **future scenarios**, background improvements are based solely on the IMAGE SSP2 RCP2.6 scenario, a middle-of-the-road scenario with medium mitigation challenges, where emissions peak before 2020 and then decline. This choice, while helpful in exploring future reduction potentials for both technologies through, for example, grid improvements, may result in somewhat optimistic outcomes given current global warming trajectories and the pace of international sustainability efforts. Additionally, premise currently only includes a subset of IAM variables (power, steel, cement, fuel production, and transport), excluding important sectors such as agriculture, heat, chemicals, and paper. In particular, changes in chemical production could significantly influence the environmental impacts of raw material production, notably for SLA under future conditions. Moreover, improvements in recycling and EoL treatment processes are not yet included in the background or foreground modelling, could potentially alter the outcomes as these technologies evolve.

Normalisation and weighing results in LCA are subject to considerable uncertainty due to data gaps and the selection of characterisation factors (Heijungs et al., 2007; Prado et al., 2020). In this study, the EF3.1 factors (Andreasi Bassi et al., 2023) were employed, which De Laurentiis et al. (2023) found the global normalisation references to yield more appropriate results compared to other approaches. However, aggregated impact results remain highly sensitive to these methodological choices, as different normalisation and weighting sets could shift the relative importance of impact categories, potentially altering the relative performance of the technologies. For example, Laurentiis et al. observed that EF3.1 factors tend to inflate normalisation values for freshwater eutrophication and land use, a contribution check showed that for this study energy resource use and material resource use became more prominent in the weighed results and land use showing low results for both (see Appendix Z, File VIII for details). In previous literature, high results for ecotoxicity and human toxicity were mentioned, but the uncertainty and data gaps were not evident in the results and remained comparatively low (Fantke et al., 2018; Heijungs et al., 2007). For the weighted results, Laurentiis et al. observed that the EF3.1 factors tend to inflate specific impact categories, particularly climate change, energy resource use, material resource use, and water use, while reducing the relative importance of ecotoxicity and human toxicity in the weighted results. These observations are consistent with the changes seen in this study from deriving the weighted results from normalisation results. Although these variations influence the relative performance of the two alternatives, the conclusions that IM exhibits lower impacts than SLA are expected to hold even if alternative normalisation and weighting factors were applied, due to its higher impacts across almost all impact categories.

6.4. Future Research

First, future studies should focus on **improving data quality** and reducing uncertainty. Researchers should update technological data by collecting information from recently released SLA printers and comparing them to smaller-scale IM machines to ensure both technological and temporal consistency. Developing detailed 3D models will help accurately measure energy use, build times, and mould sizes, thereby reducing the uncertainty caused by estimates. Moreover, incorporating uncertainty ranges for critical inputs, such as energy consumption and resin composition, and conducting global sensitivity analyses will better show data variability.

Second, **refining modelling assumptions** is essential for a more accurate assessment. Future research should explore new, low-impact resin formulations, including biobased or more readily recyclable options, to assess their effect on SLA's overall environmental footprint. Additionally, investigating the influence of using alternative plastics for IM, such as polypropylene or polycarbonate, in comparison to ABS, can provide more nuanced insights into the crossovers between IM and SLA using different materials. Additionally, dynamic models that reflect real-world demand curves for spare parts, rather than assuming a fixed storage duration, will provide a more realistic representation of inventory and overproduction impacts.

Third, **enhancements in modelling recycling** and allocation methods are needed. Researchers should integrate updated European-specific recycling data for ABS from the latest ecoinvent versions. Exploring alternative allocation methods will provide deeper insights into how these methods influence overall system performance.

Finally, **methodological refinements** in impact aggregation and expanding scenario coverage of industries in premise are important. Future work should explore alternative aggregation techniques, such as outranking procedures as suggested by Prado et al. (2020), to address potential biases inherent in the current EF3.1 normalisation and weighting factors. Expanding the set of integrated assessment model variables to include sectors such as chemicals could further refine environmental impact estimates, particularly for SLA raw material production. Additionally, testing different integrated assessment models or background scenarios will help assess how variations in future pathways might influence the comparative performance of IM and SLA, ultimately identifying conditions under which each technology might be more advantageous.

6.5. Contributions

This study makes several contributions to both the scientific community by addressing key data gaps and research priorities identified in the literature. This research extends previous studies on AM, primarily building on Prado et al. (2020) and Mele et al. (2020), by providing a comprehensive LCA that encompasses stages beyond printing, including logistical impacts of spare part provision, and situating it in the context of a more detailed assessment of IM. In doing so, it addresses critical gaps highlighted by Kellens et al. (2017), Peng et al. (2018), and Hegab et al. (2023), It also addresses critical gaps highlighted by Kellens et al. (2017), Peng et al. (2018), and Hegab et al. (2023), such as more nuanced data on resin production and exploring the potential of recycling, going beyond the common focus on energy consumption. Furthermore, by integrating spare parts inventory management with sustainability assessment, as suggested by Zhang et al. (2021), this study advances our understanding of how different production strategies (e.g., production scale, storage duration, and recycling) influence overall environmental trade-offs between IM and SLA. The scenario-based approach, which incorporates future technology developments, also responds to calls from Kokare et al. (2023) for more comprehensive and dynamic LCAs of AM technologies.

7. Conclusions

This study conducted a prospective life cycle assessment (pLCA) to assess and compare the environmental impacts of two spare part provision strategies: on-demand additive manufacturing (AM) via stereolithography (SLA) and conventional injection moulding (IM) involving long-term storage. This evaluation aims to assess the environmental implications of the European Ecodesign for Sustainable Products Directive, which requires a 10-year spare part availability for specific consumer products.

The main research question was: *"What long-term spare part provision strategy (on-demand SLA printing versus injection moulding and storage) provides the most sustainable solution for spare plastic housing components of washing machines?"*

A representative washing machine spare part was selected based on a literature review, and its suitability for AM was evaluated using AM design requirements by van Oudheusden et al. (2024), ensuring its geometric and functional compatibility with the capabilities of SLA. The SIMPL framework, developed by Langkau et al. (2023), was utilised for the systematic creation of pLCA scenarios. These scenarios were then implemented in Activity Browser, utilising Premise and ScenarioLink plugin to transform the ecoinvent 3.10.1 database based on the IMAGE SSP2 RCP2.6 scenario. The analysis incorporated key parameters, including energy efficiency, equipment lifetime, recycling practices, post-processing, overproduction, and rail transport share, as well as evaluated the effects of production scale, storage duration, and SLA recycling through a sensitivity analysis.

Key assumptions in the modelling included a 10-year storage period for IM spare parts, 24/7 operation with 10% downtime for both technologies, SLA printer lifetime of 5 years, and IM equipment lifetime of 10 years. Inputs for IM and ABS use ecoinvent 3.10.1 ecoinvent data, with approximations made for SLA resin composition. Material inputs and energy consumption for the SLA printer were based on data by Faludi et al. (2015) on the ProJet 6000HD SLA printer, while print time and the associated per-part energy impacts were estimated. IM machine data was based on Arburg (2022) on their Allrounder 570H machine, while energy use is from ecoinvent's IM process.

The results reveal that under current conditions, SLA spare parts exhibit approximately twice the environmental impact of IM with storage. However, SLA shows significant potential for reducing impact through improvements in printer efficiency, resin composition, lifetime extension, and decarbonisation of the background system. For SLA to become environmentally competitive with IM at higher production volumes, ambitious technological and material improvements are necessary. A crossover point was observed at a production volume of around 250–350 units, below which SLA becomes the environmentally preferable strategy. The impact assessment provided several key insights:

1) IM is currently the more sustainable option for high-volume spare part production.
2) SLA printing can outperform IM at small-scale spare part production.
3) Storage & overproduction contribute moderately to IM impacts but are not primary driver.
4) Decentralised production reduces transport impacts it does not outweigh impacts of AM.
5) High energy intensity of the SLA printing process remains a key hurdle.
6) Material impacts dominate across both technologies.
7) Recycling practices for both technologies are highly influential.
8) Competitiveness of SLA depends on future energy efficiency, resin innovation, and printer lifetime extension.

This study also acknowledges key limitations, such as the use of outdated IM energy data, estimated SLA print times, approximated resin compositions, fixed storage periods, and reliance on a single integrated assessment model scenario and allocation method for recycling. Despite these uncertainties, the sensitivity analyses indicate that the main conclusions, particularly regarding the relative environmental benefits of IM at scale and SLA for low volume, are robust across a wide range of assumptions.

The findings contribute to the growing body of literature on the role of AM in sustainable manufacturing and spare part logistics by offering a comprehensive, scenario-based comparative LCA that accounts for technological, storage, production scale, and prospective system changes. For manufacturers, this work offers actionable guidance on technology selection and supply chain optimisation. For AM developers, it highlights crucial areas for innovation, especially in developing sustainable resin formulations, enhancing energy efficiency, extending equipment lifespans, and exploring the potential of SLA recycling.

In conclusion, the research provides insights for sustainability-based decision-making in spare part management. It highlights that although IM is currently the more sustainable choice for high-volume production, notable advancements in stereolithography SLA may create competitive opportunities in low-volume niches in the future. Future studies should aim to enhance data inputs, broaden the range of background variables, and investigate different methods for aggregating impacts to further substantiate these findings.

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9. Appendix

Appendix A: Washing Machine Component Evaluation

Table 14: Overview of washing machine components and their potential suitability for additive manufacturing.

Group	Component	AM Suitability	Applicable Criteria
Drum	Inner Drum	Not suitable	Too large; high structural integrity required
	Drum Tub	Not suitable	Too large; high structural integrity required
	Drum Paddles	Potentially suitable	Moderate forces; smooth surface required
	Drum Spider	Not suitable	Must withstand high forces and fatigue resistance
	Ball Bearings	Not suitable	Requires high precision and material strength
Door	Door	Not suitable	Too large; requires specific materials and surface finish
	Door Hinge	Potentially suitable	Accurate fit; handles moderate forces
	Door Seals	Not suitable	Silicone material and difficult to achieve water tightness
	Door Lock	Potentially suitable	Moderate forces; fine details; accurate fit
Water Management	Drain Pump	Potentially suitable	Complex geometries; smooth surface required
	Filters	Potentially suitable	Accurate fit; smooth surface required
	Valves	Potentially suitable	Accurate fit; smooth surface required
	Aquastops	Potentially suitable	Accurate fit; smooth surface required
	Pressure Chamber	Potentially suitable	Accurate fit; smooth surface required
	Hoses (in/out)	Not suitable	Standardised, widely available
	Piping	Not suitable	Standardised, widely available
	Detergent Drawer	Potentially suitable	Fine details; smooth surface; accurate fit
	Other Seals	Not suitable	Standardised; material properties difficult to achieve
Motor	Motor	Not suitable	Advanced electronics and high mechanical demands
	Carbon Brushes	Not suitable	Requires specific carbon materials
	Drive Belt	Not suitable	Needs high flexibility and durability
	Shock Absorbers	Not suitable	High durability and mechanical performance required
Electronics	Printed Circuit Boards	Not suitable	Advanced electronic functionality
	Electronic Displays	Not suitable	Advanced electronic functionality
	Buttons	Potentially suitable	Fine details; accurate fit; smooth surface
	Pressure Switches	Not suitable	Precision and internal complexity
	Heater	Not suitable	Advanced electronic functionality; high temperatures
	Thermostat	Not suitable	Specific materials and electronic functionality
	Sensors	Not suitable	Advanced electronic functionality
	Central Control Unit	Not suitable	Advanced electronic functionality

Appendix B: Characterised Indicator Results for 2025 & 2050

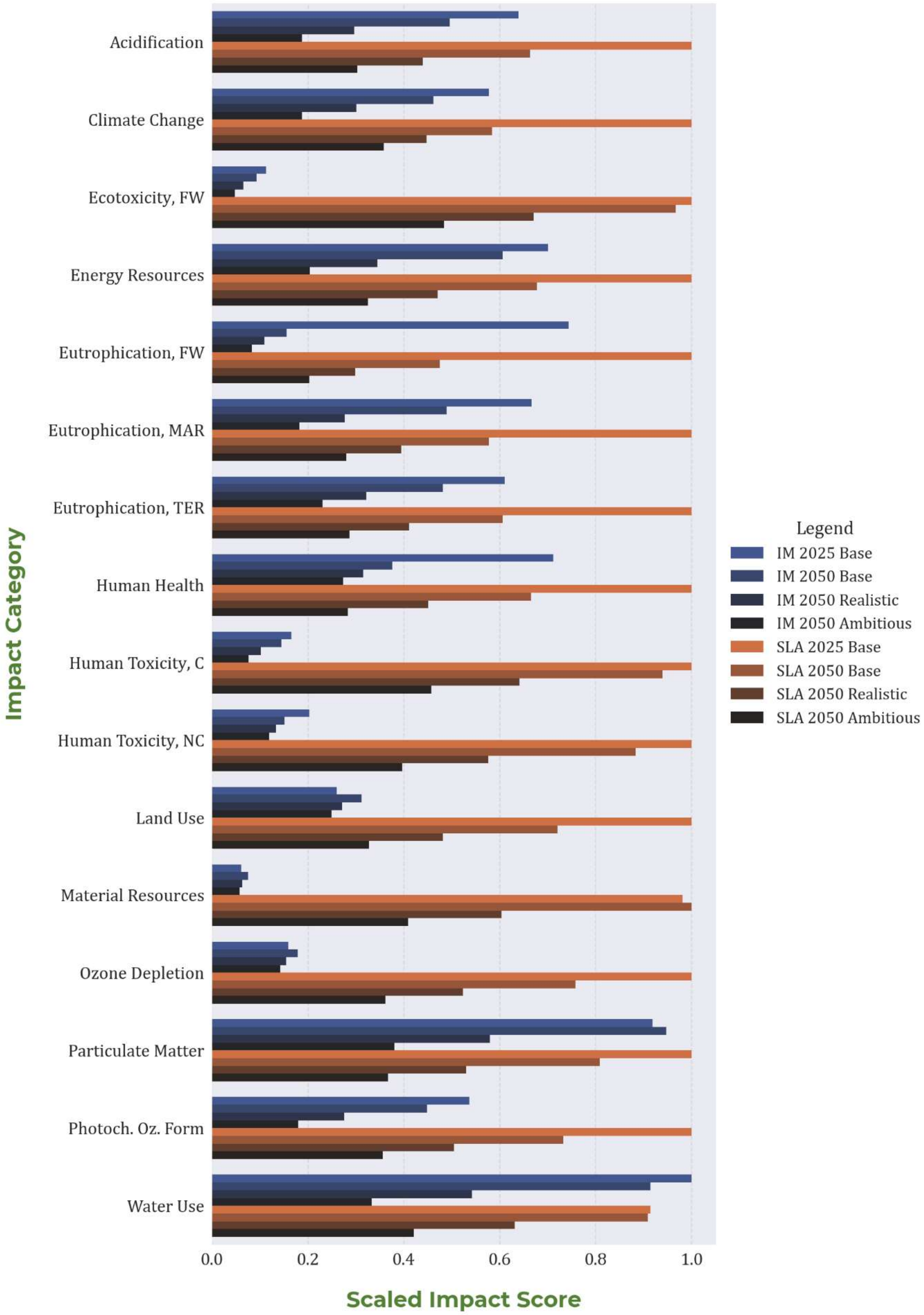

Figure 17: Characterised indicator results of injection moulding and storage of spare parts and the on-demand SLA printing in 2025 and 2050 for different scenarios, using the EF3.1 impact assessment family. Impact results per category are scaled relative to the largest reference flow.

Appendix C: Environmental Hotspot Identification

Life Cycle Stage Definitions

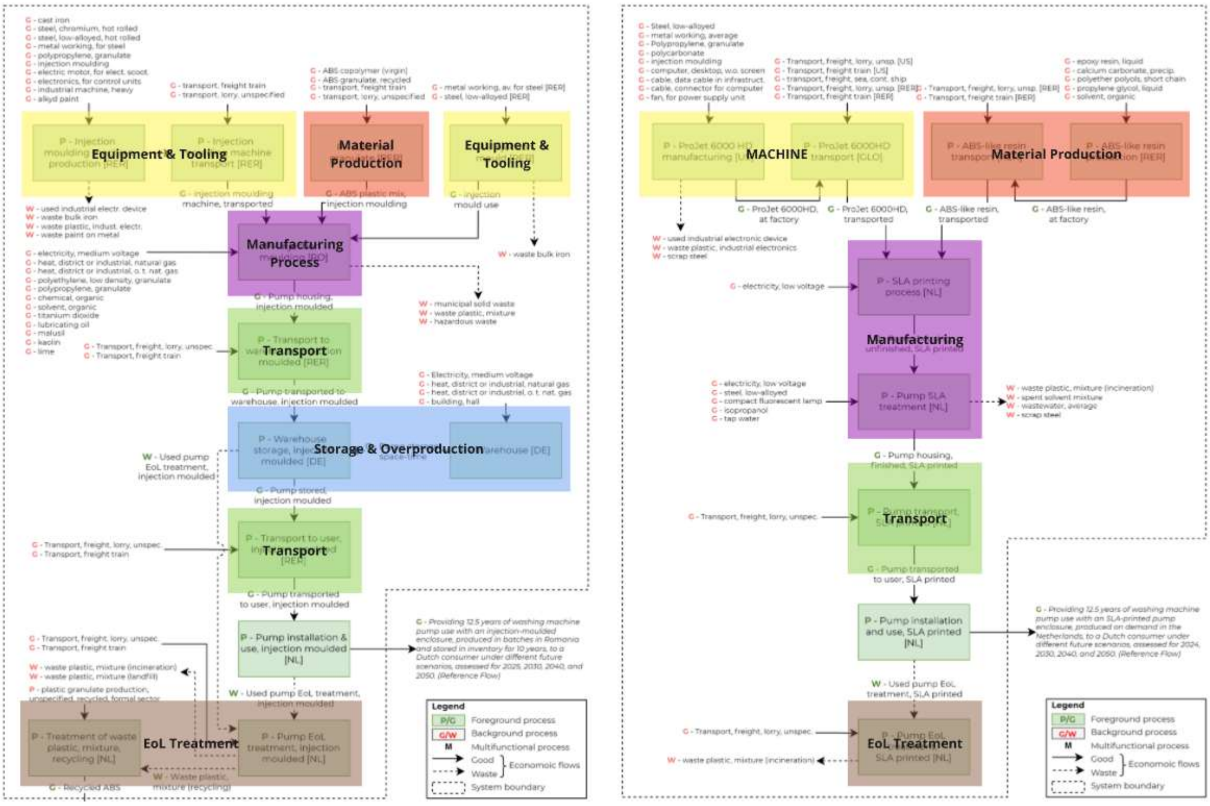

Figure 1: Life cycle stage definitions for IM and SLA.

Life Cycle Stage Calculations

Example calculation on how stage impacts were calculated:

$$Impact\ (SLA\ printing) = \ Total\ Impact\ (Printing\ 1\ Unfinished\ Pump) - (Impact\ (Resin\ Production) + Impact\ (Printer\ Manufacturing))$$

Life Cycle Stage Contributions SLA 2050 Ambitious

Table 1: Life cycle stage contributions for SLA in 2050 Ambitious scenario.

Stages - SLA 2050 Ambitious							
Impact category	**Printer**	**Resin**	**Printing**	**Treament**	**Transport**	**Use**	**EoL**
Acidification	18%	37%	20%	21%	0%	0%	3%
Climate Change	5%	25%	6%	26%	0%	0%	38%
Ecotoxicity, FW	5%	81%	3%	6%	0%	0%	4%
Energy Resources	5%	46%	17%	30%	0%	0%	1%
Eutrophication, FW	31%	29%	22%	18%	0%	0%	1%
Eutrophication, MAR	14%	40%	16%	19%	1%	0%	10%
Eutrophication, TER	14%	39%	20%	18%	1%	0%	8%
Human Toxicity, C	9%	73%	7%	7%	0%	0%	4%
Human Toxicity, NC	25%	27%	27%	13%	0%	0%	9%
Human Health	9%	29%	55%	6%	0%	0%	0%
Land Use	11%	47%	22%	16%	2%	0%	2%
Material Resources	43%	24%	22%	10%	0%	0%	0%
Ozone Depletion	6%	52%	16%	25%	0%	0%	1%
Particulate Matter	16%	44%	15%	20%	2%	0%	3%
Photoch. Oz. Form	9%	43%	13%	31%	0%	0%	4%
Water Use	8%	33%	39%	12%	0%	0%	8%
Average	14%	42%	20%	17%	0%	0%	6%

Table 2: Life cycle stage contributions share differences for SLA in 2050 Ambitious scenario vs 2025 Base.

Share Difference - SLA 2025 vs 2050 Ambitious							
Impact category	**Printer**	**Resin**	**Printing**	**Treament**	**Transport**	**Use**	**EoL**
Acidification	-4%	2%	-7%	7%	0%	0%	2%
Climate Change	-4%	-1%	-27%	8%	0%	0%	24%
Ecotoxicity, FW	-3%	2%	-2%	1%	0%	0%	2%
Energy Resources	-2%	10%	-18%	10%	0%	0%	0%
Eutrophication, FW	7%	-1%	-14%	7%	0%	0%	0%
Eutrophication, MAR	-4%	3%	-14%	7%	0%	0%	7%
Eutrophication, TER	-4%	3%	-12%	6%	0%	0%	6%
Human Toxicity, C	-4%	6%	-5%	1%	0%	0%	2%
Human Toxicity, NC	-5%	3%	-7%	4%	0%	0%	5%
Human Health	2%	-1%	2%	-3%	0%	0%	0%
Land Use	0%	18%	-30%	9%	2%	0%	1%
Material Resources	-9%	5%	0%	4%	0%	0%	0%
Ozone Depletion	0%	16%	-25%	9%	0%	0%	1%
Particulate Matter	-9%	2%	-2%	5%	2%	0%	2%
Photoch. Oz. Form	-4%	3%	-11%	9%	0%	0%	2%
Water Use	-4%	-1%	-1%	1%	0%	0%	4%

Note: Share difference has been calculated by subtracting the 2025 contribution percentage from the 2050 contribution percentage in the corresponding impact category. E.g. in the case of acidification impacts for the printer the share difference -4% = 18% (2050 Share) - 22% (2025 Share), saying that the printer contributes in relation to the total impact 4% less than in 2025. However, this is only relative and does not imply whether the printer impacts for acidification have absolutely been reduced by 4%.

Appendix D: Full Consistency & Completeness Check

Consistency Check

A consistency check was conducted to verify that data sources, assumptions, methods, and models were uniformly applied across both alternatives and aligned with the defined goals and scope.

The consistency assessment results are detailed in Table 1. Overall, findings indicate that while most elements are aligned, discrepancies in data age and technology coverage may affect their comparability. The modelling of both alternatives was approached similarly, and cut-offs, such as for factory buildings and packaging materials, were applied consistently. The proposed actions for future research emphasize addressing outdated data sources and enhancing accuracy for specific inputs. For SLA, this could involve collecting primary data on advanced SLA printers, estimating print times more precisely, and refining the resin recipe's accuracy. As for IM, improvements could be achieved through direct measurements of primary energy consumption for specific parts, adjustments in mould size and weight data, and by updating recycling data from European plants. However, these elements are out of scope for the current study due to time limitations and restricted access to better data sources. Limitations regarding comparability are discussed in the subsequent section.

Table 1: Consistency check for both alternatives.

Aspect	Check	Rating	Action
Data Sources	**IM**: Grey literature, ISO-compliant LCA with primary data (Arburg, 2024). **SLA**: Peer-reviewed literature with primary data collection (Faludi et al., 2015). **Both**: Ecoinvent, white & grey literature.	Good	No action needed.
Data Accuracy	**Machine materials**: Detailed bill of materials for both, but different collection methods (IM: primary; SLA: estimated via measurements/mass balance). **Electricity use**: SLA based on primary measurements; IM based on generic Ecoinvent data. **Raw materials**: IM uses an ABS plastic average; SLA uses an ABS-like resin, but composition is estimated using Ecoinvent proxies (limited accuracy). **Recycling** (only IM): Low accuracy as Ecoinvent India proxy was used, which does not reflect ABS recycling in Europe.	Good to Weak	No action due to no other available data.
Data Age	**IM:** Machine is current (2022); Ecoinvent electricity consumption data is outdated (2007). **SLA**: Printer and electricity consumption from 2015.	Weak	No action due to no other available data.
Technology Coverage	**Both**: Represent readily available medium-scale technologies.	Good	No action needed.
Time-related Coverage	**IM:** Represents a state-of-the-art technology (2022). **SLA:** No longer cutting-edge (2015).	Weak	No action due to no other available data.
Geographical Coverage	**All processes:** adapted to Ecoinvent market mixes in Europe (specific regions: RO, DE, NL) where possible.	Good	No action needed.

Completeness Check

No technical expert was available to directly assess the systems. Consequently, the completeness evaluation relied on comparisons with existing literature.

For the SLA alternative, the inventory mainly references Faludi et al. (2015), which concentrated on the printing process and covered printer and resin manufacturing; however, they used upper and lower estimates for resin due to limited matching Ecoinvent data. Since this research did not address post-processing, data regarding washing and curing from Mele et al. (2020) was included, acknowledging that both studies system boundaries end at the finished printed part. This model enhances these inventories by including more specific resin composition modelling and integrating case-specific transportation evaluations to the user and EoL treatment.

For the IM alternative, the process is modelled in line with the Ecoinvent process but has been regionalised and adjusted (e.g., by applying cut-offs for building and packaging) to ensure consistency with the SLA alternative. This aggregated IM process is consistent with previous studies (Elduque et al., 2015; Thiriez & Gutowski, 2006) and is further extended to encompass impacts from capital goods (machine and mould), transportation, storage, overproduction, and EoL management, thereby capturing the entire lifecycle of long-term spare part provision.

Finally, it should be noted that some emissions stemming from this system lack characterisation factors in the EF3.1 method. While 518 biosphere flows are uncharacterised (excluding flows with zero reference values), this figure is lower compared to the 1,011 missing flows in ReCiPe 2016 v1.03 and 1,484 in CML v4.8 2016, confirming that EF3.1 offers the broadest coverage for this assessment.

Appendix E: Sensitivity Parameter Reductions

Table 1: Sensitivity parameter reductions for IM

	Relative Parameter Reductions, IM					
Impact category	**Background**	**Recycling Inputs**	**Machine Efficiency**	**Overpro-duction**	**Rail Transport**	**EoL Treatment**
Acidification	-22.4%	-44.6%	-1.2%	-1.2%	-7.8%	0.7%
Climate Change	-20.2%	-43.9%	-0.5%	1.2%	-7.7%	-1.7%
Ecotoxicity, FW	-17.9%	-40.1%	-1.0%	0.3%	-7.5%	2.4%
Energy Resources	-13.5%	-53.3%	-1.5%	-1.0%	-9.6%	0.9%
Eutrophication, FW	-79.1%	-6.7%	-2.3%	-0.3%	-2.2%	0.5%
Eutrophication, MAR	-26.6%	-36.6%	-0.9%	0.6%	-6.1%	-6.7%
Eutrophication, TER	-21.0%	-37.5%	-0.8%	-2.2%	-6.1%	0.5%
Human Toxicity, C	-12.9%	-37.9%	-1.2%	-1.2%	-7.8%	1.7%
Human Toxicity, NC	-25.5%	-13.7%	-2.2%	-0.1%	-7.1%	4.6%
Human Health	-47.3%	-1.1%	-10.9%	-1.4%	-4.8%	2.0%
Land Use	20.0%	-11.0%	-1.8%	-5.9%	-9.1%	1.6%
Material Resources	23.6%	-19.7%	-2.5%	-5.8%	-10.0%	5.5%
Ozone Depletion	12.7%	-13.1%	-1.9%	-4.9%	-9.3%	3.7%
Particulate Matter	3.1%	-55.3%	-0.5%	-1.7%	-12.1%	0.7%
Photoch. Oz. Form	-16.4%	-47.0%	-0.7%	-1.0%	-8.3%	0.8%
Water Use	-8.6%	-53.3%	-1.7%	-0.9%	-9.8%	0.6%
Average Reduction	-15.7%	-32.2%	-2.0%	-1.6%	-7.8%	1.1%

Table 2: Sensitivity parameter reductions for SLA

	Relative Parameter Reductions, SLA						
Impact category	**Background**	**Printer Lifetime**	**Resin Impact**	**Printer Efficiency**	**Solvent Reduction**	**Curing Efficiency**	**Rail Transport**
Acidification	-33.7%	-10.1%	-11.3%	-9.0%	-5.4%	-0.1%	-0.2%
Climate Change	-41.7%	-3.2%	-9.0%	-3.1%	-7.1%	0.0%	-0.2%
Ecotoxicity, FW	-3.3%	-4.6%	-39.0%	-2.4%	-2.3%	0.0%	0.0%
Energy Resources	-32.2%	-3.3%	-15.0%	-8.3%	-8.5%	-0.1%	-0.2%
Eutrophication, FW	-52.6%	-11.9%	-5.8%	-6.7%	-2.8%	-0.1%	0.0%
Eutrophication, MAR	-42.3%	-7.3%	-11.1%	-6.9%	-4.2%	-0.1%	-0.2%
Eutrophication, TER	-39.4%	-7.8%	-11.1%	-8.6%	-4.2%	-0.1%	-0.2%
Human Toxicity, C	-6.1%	-7.9%	-33.2%	-4.7%	-2.4%	-0.1%	-0.1%
Human Toxicity, NC	-11.6%	-18.6%	-10.7%	-16.0%	-2.9%	-0.2%	-0.5%
Human Health	-33.4%	-5.1%	-8.1%	-23.5%	-1.2%	-0.3%	0.0%
Land Use	-28.0%	-7.2%	-15.9%	-10.8%	-4.5%	-0.1%	-1.7%
Material Resources	1.9%	-34.1%	-9.9%	-13.9%	-2.2%	-0.2%	-0.2%
Ozone Depletion	-24.3%	-4.1%	-18.6%	-8.8%	-7.7%	-0.1%	-0.3%
Particulate Matter	-19.2%	-11.3%	-17.0%	-8.4%	-6.1%	-0.1%	-2.4%
Photoch. Oz. Form	-26.8%	-6.1%	-15.1%	-6.7%	-9.5%	-0.1%	-0.3%
Water Use	-0.6%	-6.8%	-14.9%	-27.0%	-4.3%	-0.3%	-0.1%
Average Reduction	-24.6%	-9.3%	-15.4%	-10.3%	-4.7%	-0.1%	-0.4%
Weighed Reduction	-19.6%	-4.3%	-25.1%	-6.1%	-5.3%	-0.1%	-0.3%

Appendix Z: Excel Files

The following files can be found in the supplementary data:

- **File I: Life Cycle Inventory Data**
- **File II: Life Cycle Inventory Calculations**
- **File III: Scenario Difference File - Main**
- **File IV: Impact Assessment Results for All Years and All Scenarios**
- **File V: Life Cycle Stage Contribution Calculations and Results**
- **File VI: Scenario Difference File - Sensitivity**
- **File VII: Sensitivity Analysis Calculations & Results**
- **File VIII: Normalisation, Weighing Factors and Contribution Analysis Results**