

Article

Multi-Domain Assessment of Thermomechanical Recycling Based on Bio-Based and Petroleum-Based Additively Manufactured Components

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Abstract: The surge in global population growth and the escalating demand for social and economic prosperity present formidable challenges in the 21st century. However, asserting the sustainability of some ecological impact reduction initiatives, such as recycling, requires a comprehensive evaluation within various domains, including performance, ecology, and economics, and contemporary advancements in integrating quantitative assessments of material and manufacturing properties, coupled with mathematical decision-making approaches, contribute to mitigating subjectivity in determining the efficiency of recycling. This paper implements a robust multi-criteria decision-making (MCDM) approach to address the complexities of recycling, validating its implementation and effectiveness through a case study. The focus is set on the application of bio-based polylactic acid (PLA) and petroleum-based polypropylene (PP) additively manufactured (AM) parts produced through Fused Filament Fabrication (an approach to ecology/performance domains). The work introduces a cost analysis focusing on calculating thermomechanical recycling within the economic domain. The well-known Analytical Hierarchical Process (AHP) provides a structured framework for decision-making (the ecological impact domain) with the focus being on application. The assessment or recycling viability, encompassing AHP calculations, preprocessing, and supplementary tools, is provided by developing an open-source software tool for practitioners in the field of material science and manufacturing. The results indicate a preference for industrial-scaled recycling over virgin or lab-recycled manufacturing, particularly for petroleum-based polypropylene. The versatility and simple utilization of the software tool allow seamless integration for diverse use cases involving different materials and processes.

Keywords: sustainable engineering; recycling; analytical hierarchical process; multi-criteria decision-making (MCDM); additive manufacturing



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1. Introduction

The origin of commercial plastics can be backdated to the 1950s, although demand and consumption have risen steadily to this day. The annual production of plastics amounts to over 400 Mt (2022) with an increasing tendency [1,2]. The success story is explained through the extreme versatility in production and application processes caused by polymer properties along with the low-cost production of a high-volume demand of material class [3]. Amongst principal polymer groups, thermoplastics lead demand with 90% of all polymers globally produced. One of their key properties is the ease of forming to generate three-dimensional geometries [4]. Some of the manufacturing processes that have been gaining much attention incorporate the different production technologies of Additive Manufacturing (AM). Fused Filament Fabrication (FFF) especially attracts a wide population segment, from enthusiastic hobbyists to professional academics [5,6]. This bottom-up approach to the democratization of production manufacturing allows a quick realization of geometrical and functional prototypes with a variety of materials. Recent advances in technology and material development have led to low-cost machinery acquisition and application scenarios [7,8]. Advantages include a theoretical waste-free process. However, economic constraints must be taken into account when considering larger batch sizes. Considering the thermoplastic properties of the polymers used for extrusion-based AM processes, multiple elementary formation and melt-down cycles seem possible. Once more, it is necessary to slow, narrow, or even close the loop of resources in view of the global challenges [9]. The steady growth of the world population, the demand for continuous economic growth, and the decreasing half-lives of technological trends and products suggest rising consumption behavior [10]. Our planet's capacity is not able to regenerate quickly enough in the face of this long-term development [11]. Fossil resources as a foundation for important petroleum-based products and energy processes are limited but essential components in our present society. The plastic industry claims 8% of the globally extracted raw oil for production purposes [12]. In parallel, exponential growth in plastic production and waste generation with low recycling rates dramatically increase future challenges [13].

At a technological level, knowledge gaps, collecting and sorting issues, and the degradation behavior (modification of the polymer chains and branching affected by the exposure of external sources like thermomechanical forces, UV light, water uptake, etc.) of plastic-based products can be considered as main bottlenecks for this poor ratio [14]. At a socio-cultural level, societal consciousness, lack of knowledge, corporate society's structure/architecture, the pace of life, and the environmental designs of cities and regulative norms are key factors and limitations to accelerate sustainable behavior towards conscious and structured recycling [15–17].

Despite the academic, commercial, legislative, environmental, and social efforts to face this problem and reduce the impact through closing-loop strategies, it is an enormous task alone to find solutions for recycling strategies in the isolated domains:

1. How can a society or the individual be educated or supported to integrate a favorable behavior regarding the correct initiation of product recycling after the End-of-Life (EoL)?
2. How can privatized or governmental recycling logistics function on economic, technological, environmental, administrative, and structural (regional, national, international) levels?
3. How can manufacturing processes work at a technological level in view of recycling bottlenecks through decomposing, sorting, cleaning, and remanufacturing? How can different waste sources (post-consumer, post-industrial) be integrated?

4. How can these manufacturing processes be evaluated and compared regarding virgin production at an environmental level?
5. How can different material types (petroleum-based vs. bio-based materials) be evaluated and compared?
6. How can the physical properties/performance of recycled materials be standardized and be competitive?
7. How can the economic properties/performance of recycled materials be standardized and be competitive?
8. Which quantitative indicators (physical, ecological, economic, and processing performance) are suitable for evaluating the individual domains?
9. This leads to the overarching question: How can any type of recycling (thermomechanical, chemical, etc.) be quantitatively assessed or compared against a linear process or against each other from a holistic perspective?

2. Rationale of This Research

Considering the complexity and depth of the proposed eight questions, the presented work will only investigate questions 4, 8, and 9 in detail. The focus is set on question 8 with a multi-domain assessment based on a case study regarding additively manufactured bio-based and petroleum-based components. The following section defines the research background and motivation, as well as the potential research gap. Last, the research objectives and contributions, as well as the manuscript structure, are highlighted.

2.1. Research Background and Motivation

The state-of-the-art section is structured into plastic industry and recycling at a global level, the evaluation of performance parameters within the recycling context, and AM and recycling. A cross-section of MCDM research in combination with sustainability is presented.

2.1.1. Plastic Industry and Recycling as a Global System

Nowadays, the plastic industry, including the return of end-of-life materials, can be understood as a complex global system. A system can be defined as “an assemblage or combination of functionally related elements or parts forming a unitary whole” [18]. In contrast, the output of a system leads to emergent behavior [19] and not just the functional sum of its entities. Research is ongoing to understand the macroeconomic processes and interactions of this complex area. Iacovidou et al. applied systems thinking to the Circular Economy (CE) field and identified five key components to integrate them into an actor–process–value flow: “resource flows and provisioning services, regulatory frameworks and political landscape, business activities and the market, infrastructure and innovation, and user practices” [20]. Another work [21] applied a material flow analysis of the 27 EU countries including ten polymers from nine sectors to model the EU plastic value chain. Nevertheless, to understand the role of high-level recycling mechanisms, a screening of the international oil price, the plastic stock index, the plastic recycling market, and their connectivity is mandatory [22]. From an economic perspective, the development of the crude oil price (dependent on the magnitude and accessibility of the reserves and global market behaviors) influences the price of virgin plastic and, consequently, the competitiveness and necessity for plastic recycling activities. Predictions of oil prices and volatility [23,24] are performed, as well as estimations regarding total oil and gas reserves [25]. Results from Owen et al. have claimed a permanent petroleum deposit [26]. However, due to complicated access, the market will shift from a demand-driven to a supply-constrained market, potentially leading to higher prices. Additional events such

as COVID-19 or the war between Ukraine and Russia may also impact crude oil and virgin plastic prices in the short-to-medium term [27]. From ecological and economic perspectives, combining recycling with a higher biomass content, a circular bioeconomic approach, can turn the plastic production sector into a net carbon sink and reduce raw material consumption [28].

2.1.2. Evaluation Parameters of Recycling

At the material level, the parameters for evaluating recycling can vary depending on different perspectives: (i) field of performance properties (e.g., functional performance—mechanical) (ii) the type of material (e.g., thermoplastics—polypropylene), (iii) the recycling process (e.g., thermomechanical recycling), and (vi) the recycling logistics (e.g., collection and sorting). Volk et al. investigated four lightweight packaging plastics (PP, PE, PVC, and PS) regarding their recycling processes (mechanical, chemical, and pyrolysis) considering the global warming potential, the Cumulative Energy Demand, the carbon efficiency, and the product costs [29]. The market inefficiency regarding the implementation of recycling was parametrized by Mroueh et al. [30] by integrating the transaction costs in secondary material markets; information failures related to waste quality, consumption externalities, and risk aversion; technological externalities related to products; and market power in primary and secondary markets. Demets et al. provided a scoring approach to evaluate the recycling quality based on the physical resource potential, resource recovery efficiency, functional performance, and the market response, as well as an overview of single quantitative parameters addressing mechanical failure (e.g., yield strength), stiffness (e.g., Young's modulus), toughness (Charpy impact strength), processability (MFR), and further parameters [31]. Hestin et al. proposed a focus on the EU targets in terms of environmental, economic, and social impacts along the EoL processes (collection to recycling/energy recovery/landfilling) of plastics [32]. A comprehensive overview of parameters and assessment options (micro- to macro-level) in terms of polymer recycling was compiled by Badia and Amparo [33]. General characterization options focus either on performance-driven (tension, flexion, shear, etc.), process-influencing (MFI, rheometry, etc.), degradation (composting, photo-oxidation, etc.), and application-driven characterization (optics, friction, etc.) or standalone aspects like costs and ecological valorization assessment. Moreover, various environmental classification parameters, such as LCA [34,35], quality and environmental management [36], the ecological footprint [37], the carbon footprint [38], and the water footprint [39], can also be used to investigate the advantage of recycling by considering environmental aspects.

2.1.3. Recycling and Additive Manufacturing

By proposing a case study performed on Fused Filament Fabrication (FFF) and its recycling potential, a short overview of literature sources regarding filament recycling is provided. Studies on the filaments used (PP and PLA) for extrusion-based thermomechanical recycling are readily available [40–47]. Especially, PP has shown suitable parameters, even after multiple recycling cycles [46–48], whereas some properties of PLA have decreased [49,50]. Different degradation progresses (i.e., hydrolysis) can be the reasons for the changes in the molecular weight, cross-linking, chain scission, and chain cleavage [51–53]. Badia and Amparo presented an overview of quantification and qualification parameters [33]. The total cost of a complete print job includes parameters such as the total construction time, indirect costs per machine hour, the total weight of the part under construction, the price per kg of raw material, the total energy consumption, and the average electricity price [54,55]. In terms of AM, research fields regarding sustainability focus mostly on the potentials, advantages, and implementations of the process [56–59] or the pro-

cess evaluation in general [60–62], mostly in comparison with conventional manufacturing. A study combining recycling and LCA showed benefits for the environment [63].

2.1.4. MCDM and Sustainability

The complex assessment of the usefulness of recycling compared to the use of virgin materials seems to be a challenging task. An appropriate solution can be achieved through quantified multi-criteria decision-making. This widely used procedure supports a decision-making process by evaluating a range of alternatives, considering various, often contradictory, criteria. The multiple criteria are weighted to rank the preferences. Different weighting and comparing settings/calculations lead to a magnitude of various MCDM methodologies such as TOPSIS, Weighted Sum, AHP, Best-Worst Method, VIKOR, and many more [64]. Additionally, Fuzzy Logic [65] and Grey System Theory (GST) [66] can be implemented.

More recent approaches include the integration of machine learning (ML) [67,68], multi-view graph clustering [69], multi-criteria group decision-making [70], and the importance of the cause–effect relationships of factors in complex systems (HISA) [71] with the aim to reduce subjectivity, integrate interconnectivity, and improve optimization.

Due to the complexity of a comprehensive sustainability assessment, MCDM seems to be an appropriate tool for sustainability assessment in fields such as civil engineering, infrastructure, and supply chain management. Ulukan and Kop combined LCA with MCDM in transport and logistics [72]. Other studies [73,74] proposed multi-attribute decision methods in the context of sustainable manufacturing. Furthermore, appropriate material selection regarding performance or ecology-driven factors can be supported by applying MCDM [75–79]. Also, various research studies were conducted at product [80,81] and system levels (Circular Economy) by merging MCDM and sustainability aspects. Marks et al. applied MCDM to sustainable agriculture [65]. A comprehensive overview of MCDM for sustainable engineering tasks was provided by Jamwal et al. [73]. Gomes et al. proposed MCDM applications for different recycling processes investigating the criteria of investment, operational costs, treatment costs, CO₂ emissions, corporate image, and benefits [82].

2.2. Research Objectives and Contributions

Based on the existing literature, the following research gaps (RGs) were identified, defining the research objectives (ROs) and the resulting contributions (RCs):

1. Based on the highlighted research addressing recycling in isolated areas, a multi-criteria decision support framework towards a more comprehensive sustainability assessment (RG) has been aligned. Thereby, the authors want to address the usefulness of recycling based on several domains (physical, process-impacting, environmental, and economic) along the manufacturing steps of the recycling cycle (RO). This supports the assessment of sustainability from a holistic perspective (RC).
2. Most incentives regarding MCDM in the context of sustainability assessment concentrate on the ecological and technological domain (RG). In addition to the quantification of physical, process-influencing, and environmental parameters based on standardized measurements, the integration of cost factors along the various steps of the recycling process is implemented and calculated. This process is supported by measurement data (RO). This approach creates a basic framework for calculating the cost items of the individual manufacturing steps along the recycling process (RC).
3. An arithmetically understandable tool and computational framework would be beneficial for material and manufacturing engineers (RG). A software tool will be developed for the flexible and automated assessment of the usefulness of recycling (scalar sus-

- tainability end score of each alternative). It will include the calculation of the AHP, the preprocessing of the measurement data, and a single- or multiple-material cost calculation script (RO). Therefore, any expert or non-expert engineer can compare material- or product-specific alternatives for cross-functional sustainability performance (RG).
- An in-depth evaluation of bio-based and petroleum-based AM parts is missing in the literature (RG). The proposed case study backed up by quantified data aims to present a comprehensive application of the MCDM approach regarding material recycling (RO). This supports an application-based scenario with valid insights for both the AM research landscape and applied MCDM research.

The proposed model shows an approach (Figure 1) in which experienced or non-expert engineers (I) analyze whether their recycling cycles can be evaluated quantitatively. A detailed model description and system boundaries of the recycling scenario are then defined (II).

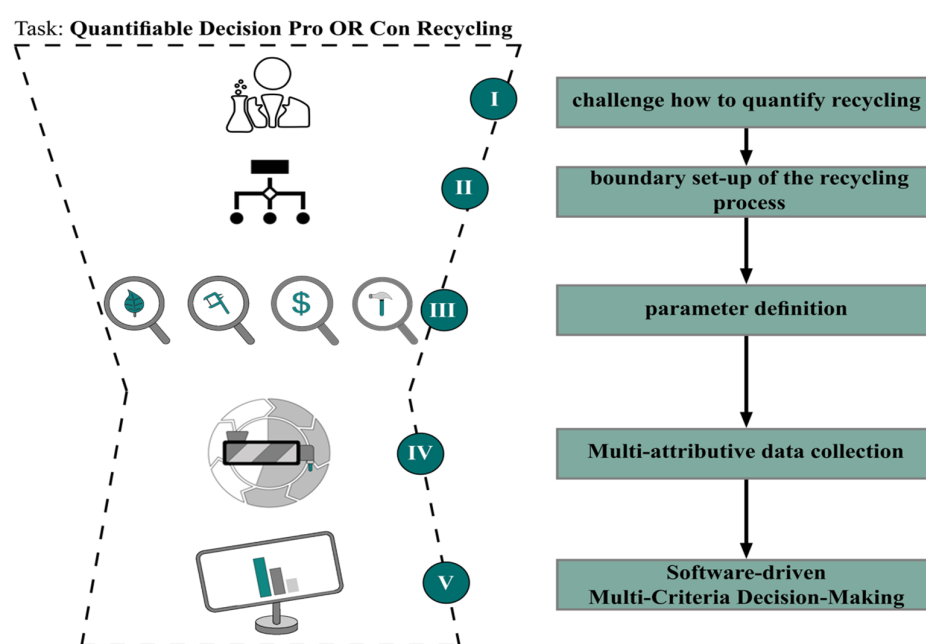


Figure 1. Proposed decision-making approach to assess the meaningfulness of recycling based on multi-attributive, quantifiable data.

Generating a range of different quantifiable parameters (III) is essential to collect comprehensive data from different, sometimes contradictory, areas. The recycling process and physical measurement (IV) of the proposed parameters are then initiated and the results are integrated into a multi-attribute decision model. Finally, the implementation of the decision model in a software tool (V) is essential to accelerate and automate decision-making processes.

2.3. Manuscript Structure

The scientific work is represented by the Materials and Methods section elaborating on the overall approach, the foundations of the data, and the cost calculation approach. Last, the AHP approach and its computational implementation into the software tool are explained. The result section includes the general description of the proposed framework, the cost calculation results, and the software implementation and concludes with the application in terms of use cases. An in-depth discussion of the results is followed by a final summary of the work.

The technical implementation and experimental validation of the model focus on the thermomechanical recycling of extrusion-based AM components. As part of the study, a simple cuboid geometry is printed from bio-based polylactic acid (PLA) and petroleum-based polypropylene (PP) and the material parameters are examined. Additionally, PP carrier and polyvinyl alcohol (PVA) structures support more complex geometry equivalent to the basic PP and PLA filament. A life cycle assessment (LCA) based on ISO 14040/44 is carried out for both geometries as well as for the virgin and secondary production cycles [83,84]. In addition, standardized mechanical (DIN ISO 527) [85], rheological (ISO 1133) [86], and process-influencing (ovality, diameter) parameters, as well as cost analyses for the thermomechanical recycling process, are measured to quantify the usefulness of recycling (final score of the material alternatives after MCDM calculation). The implementation of an Analytic Hierarchical Process as a software module ensures a value-based interaction of the various parameters. The progressive interaction with the above-mentioned methods serves to clarify important technological and evaluation-based questions in sustainable engineering.

3. Materials and Methods

3.1. General Assessment Approach

Material recycling can help overcome major ecological and climatic challenges. In addition, it can strengthen resource independence and enable the implementation of closed material cycles. Unfortunately, no workflows or tools have been suggested that enable a comprehensive comparison of virgin and recycled material. Therefore, the proposed work aims to address this problem and provide a comprehensive approach (Figure 2) with a software tool for automation. This paper investigates this goal through a conducted case study on AM and FFF filaments. The materials selection includes a bio-based PLA filament and a petroleum-based PP filament. A simple cuboid, a more complex impeller geometry, the recycled material, and the test specimen were printed with both filament types, with additional filaments (PVA and PP carriers) acting as support structures for the complex impeller shape. Since PVA is a water-soluble carrier material, only the tear-off PP carrier filament was reprocessed in the recycling process. Analogous to the virgin process, all shapes were printed with the recycled filaments after thermomechanical recycling. Both virgin and recycled materials were evaluated based on process feasibility, functional quality, sustainability, and economic viability. Appropriate parameters were chosen according to the domains in order to represent the domain quantitatively.

The measured values were directly incorporated into the multi-attribute decision-making approach, in which the individual values of each alternative were intended to answer whether recycling these filaments made sense or not. The comparison of the alternatives included simple and complex geometry for the bio-based PLA and petroleum-based PP filaments. The alternatives for each filament type included a virgin product, a recycled filament in the sense of laboratory-scale recycling with primary data, and an industrially recycled filament as an upscaled version of laboratory-scale recycling based on industrial data. To demonstrate the versatility of the software approach, a combination of the two different materials applied to the complex geometry was added. Two different high-level weighting variations are proposed in the appendix to illustrate the change in results due to preference shifting. The goal of the software implementation focused on the use of most of the multi-domain assessment tasks within and outside of multi-domain sustainability assessments.

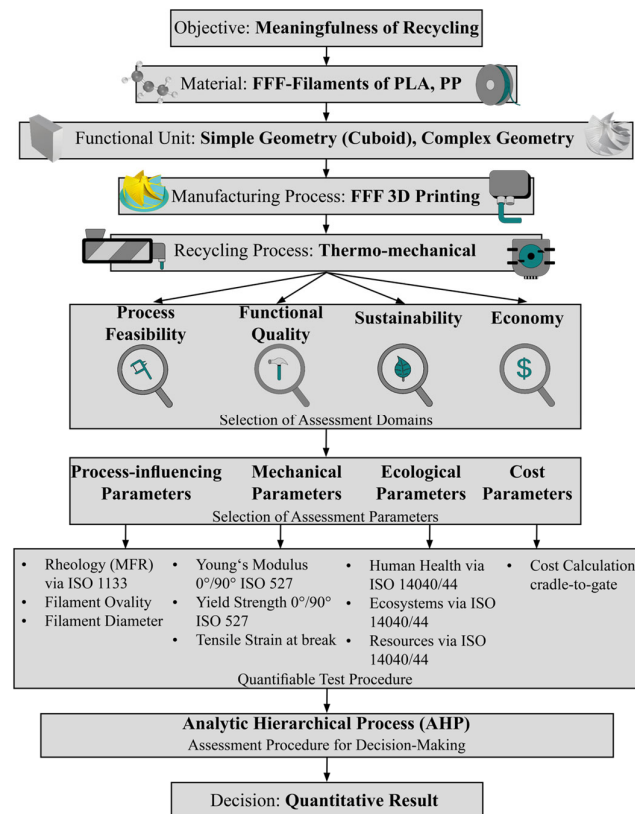


Figure 2. Performed research methodology defining the investigated material and geometry, the recycling process, the assessment domains with the corresponding parameters and their measurement standards, and the multi-attributive decision-making method.

3.2. Data Acquisition

3.2.1. Mechanical Data

The measurement of the mechanical data was based on tensile tests according to ISO 527-3B [87]. Parameters recorded included Young's modulus, fracture strain, and yield strength. All three parameters were measured at 0° and 90° to the direction of the 3D-printed layers. These values (Table 1) were adopted from previous studies [88]. Both *lab-recycled* (laboratory-scaled data) and *ind-recycled* data (industrial-scaled data) were derived from the same measurement. The mechanical values also did not differ between the simple and complex scenarios.

Table 1. Mechanical data (Young's modulus, tensile strain at break, and yield strength) via ISO 527 in 0° and 90° printing directions of the investigated polymers (virgin, lab-recycled, and industrial-recycled PLA and PP) [88].

	PLA			PP		
	Virgin	Lab-Recycled	Ind-Recycled *	Virgin	Lab-Recycled	Ind-Recycled *
0° printing direction						
Young's Modulus [MPa]	2971	2836	2836	445	500	500
Tensile strain at break [%]	3.6	6	6	1697	1929	1929
Yield strength [MPa]	52	53	53	16	17	17
90° printing direction						
Young's Modulus [MPa]	2724	2404	2404	410	424	424
Tensile strain at break [%]	1.9	1.6	1.6	659	614	614
Yield strength [MPa]	40	33	33	13	15	15

* All industrial-recycled values were transferred from experimental lab-recycled values.

3.2.2. Processing Data

Process-influencing data included the diameter and the ovality of the filament, as well as the Melt Flow Rate (MFR) according to ISO 1133. All values (Table 2) were based on previous investigations [88].

Table 2. Process-influencing data (diameter, ovality, and MFR via ISO 1033) of the investigated polymers (virgin, lab-recycled, and industrial-recycled PLA and PP) [88].

	PLA			PP		
	Virgin	Lab-Recycled	Ind-Recycled *	Virgin	Lab-Recycled	Ind-Recycled *
Diameter of filament [mm]	1.76	1.72	1.72	1.72	1.69	1.69
Ovality [-]	0.01	0.01	0.01	0.03	0.02	0.02
MFR [g/10 min; 2.16 kg; 230 °C]	29.69	55.03	55.03	8.56	8.30	8.30

* Industrial-recycled values were transferred from experimental lab-recycled values.

3.2.3. Ecological Data

The ecological data comprised the endpoint scores (human health, resources, ecosystems) of life cycle assessment (LCA) according to ISO 14044 [84]. The values adopted from Bay et al. were split into the LCA performed on the simple geometry (Table 3) and the LCA performed on the complex geometry [89]. The different values between lab and industrial recycling resulted from the scaling approach towards a more industry-real approximation.

Table 3. Ecological data (endpoint impact scores of ReCipe 2016: human health, ecosystems, resources) via ISO 14040/44 [83,84] regarding the 3D printed simple geometries (cuboid, impeller) of the investigated polymers (virgin, lab-recycled, and industrial-recycled PLA and PP) [89].

	Virgin	PLA Lab-Recycled	Ind-Recycled	Virgin	PP Lab-Recycled	Ind-Recycled
cuboid geometry						
Human health [mPt]	59.1	83.6	68.0	42.5	53.2	43.1
Ecosystems [mPt]	42.3	55.6	44.0	30.3	37.2	31.4
Resources [mPt]	46.6	65.8	52.9	41.7	42.9	35.2
impeller geometry						
Human health [mPt]	878.8	993.2	666.9	350.4	419.5	283.6
Ecosystems [mPt]	472.4	510.4	350.7	190.5	222.5	154.3
Resources [mPt]	820.5	925.7	488.5	338.6	305.6	207.6

3.3. Cost Calculation

This section presents a model to estimate the cost of the recycling process (including each single process, material, and machine), which can be used as a node in the AHP process. Since cost data are expensive to collect in advance, modeling allows them to be incorporated effectively as an important component in decision-making.

The cost model approach of Yim and Rosen [90] was used to estimate the costs C_{total} of the corresponding recycling processes C_i to manufacture a re-extruded filament (Equation (1)). A support script was provided as part of the software package for the calculation based on a sample spreadsheet.

$$C_{total} = \sum_i^n C_i \quad (1)$$

The model included the machine purchase costs (P), operational costs (O), material costs (M), and lab expenditures (L). The model could be extended to include maintenance costs (PM) if data were available.

$$C_i = P_i + O_i + M_i + L_i + [PM_i] \quad (2)$$

The machine purchase costs P_i of each machine P_{type} (Equation (3)) were computed (Equation (4)) by the purchase price of the machine P_{Purch} , the production time T_{Prod} , and the purchase costs per hour with the assumption of 95% of machine up time, 24 h, and 365 days per year during the lifetime Y_{life} .

$$P_i = \sum_i^n P_{type} \quad (3)$$

$$P_{type} = \frac{P_{Purch} \times T_{Prod}}{0.95 \cdot 24 \cdot 365 \cdot Y_{life}} \quad (4)$$

The operational costs O_i were summed up by the costs of the singular processes O_{steps_i} along the manufacturing line (Equation (5)). Furthermore, each singular process contained the costs for all sub-steps $\sum_i^n O_{substeps_i}$ during preprocessing O_{Pre} , the actual manufacturing process O_{Pro} , and the postprocessing O_{Post} .

$$O_i = \sum_i^n \sum_j^m O_{steps_j} = \sum_i^n O_{Pre} + \sum_i^n O_{Pro} + \sum_i^n O_{Post} \quad (5)$$

For example, each singular process of one operational preprocessing step O_{Pre} was summed up by the costs (Equation (6)) of each sub-step $O_{substeps_i}$.

$$O_{Pre} = \sum_i^n O_{substeps_i} \quad (6)$$

The elementary costs of each sub-step were calculated from the production time T_{Prod} multiplied by the operation rate C_O (Equation (7)); these could be either the energy costs or customer-specific costs.

$$O_{substeps_i} = T_{Prod} \cdot C_O \quad (7)$$

The total material costs of one M_i were summed up by the costs for each single material/resource M_{type_i} used during the manufacturing process (Equation (8)) including support materials not included in the final structure.

$$M_i = \sum_i^n M_{type_i} \quad (8)$$

The detailed calculation of M is shown in Equation (9). It involves the number of functional units N , their volume V , the material density ρ , and material rate per unit weight (C_m).

$$M_{type} = V \cdot C_m \cdot \rho = m \cdot C_m \quad (9)$$

The labor costs L_i are calculated analogously to the operational costs. They consist of the costs for each manufacturing step L_{steps_i} (Equation (10)), which include the preprocessing L_{Pre} , the actual process L_{Pro} , and the postprocessing step L_{Post} . Analogous to the operational costs, each step such as the preprocessing lab L_{Pre} (Equation (11)) is summed by the costs of each sub-step $L_{substeps_i}$.

$$L_i = \sum_i^n \sum_j^m L_{steps_j} = \sum_i^n L_{Pre} + \sum_i^n L_{Pro} + \sum_i^n L_{Post} \quad (10)$$

$$L_{Pre} = \sum_i^n L_{substeps_i} \quad (11)$$

Finally, the sub-steps are calculated (Equation (12)) by multiplying the labor time T_L with the lab rate C_L .

$$L_{substeps_i} = T_L \cdot C_L \quad (12)$$

The maintenance cost PM_{i_j} as the sum of the maintenance costs corresponding to each machine $PM_{machine_{i_j}}$ can be included in the module (Equation (13)).

$$PM_i = \sum_i^n PM_{machine_i} \quad (13)$$

$PM_{machine_i}$ is calculated (Equation (14)) by the total acquisition costs of each spare part PM_{spare_i} and the corresponding laboratory costs for installation. The other parameters are taken from Equation (4).

$$PM_{machine_i} = \frac{[\sum_i^n PM_{spare_i} + \sum_i^n T_L \cdot C_L] \cdot T_{Prod}}{0.95 \cdot 24 \cdot 365 \cdot Y_{machine_{life}}} \quad (14)$$

All economically relevant data for the single processes (shredding, extrusion, pelletizing, conditioning) were either measured and calculated or obtained from industry contacts or suppliers. Detailed protocols (lab and industrial recycling) of all implemented values and their corresponding sources are listed in Supplementary Materials at Tables S1 and S2.

3.4. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a decision-making support tool for complex, unordered data [91]. It relies on hierarchically structuring (Figure 3) the criteria and the pairwise comparisons of each other in the corresponding hierarchical levels. The AHP was originally developed for management decisions and has been applied to related fields from operations management over flood management to robotic systems [92–94].

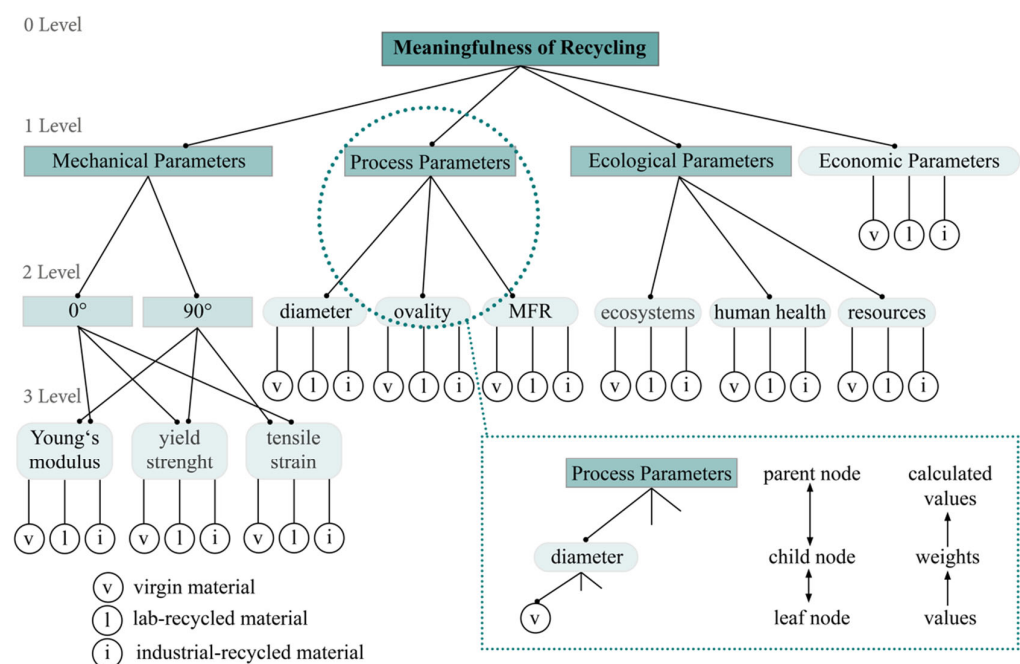


Figure 3. Example of AHP structure: The bottom level (leaf nodes) contains only value vectors for the alternative virgin material (v), lab-recycled material (l), and industrial-recycled material (i), which are normalized to be between 0 and 1. Each higher node only contains a weight matrix, which relates the influence of its respective child nodes. During tree processing, the values for the alternatives are propagated up based on the (calculated) value-weight node through the tree following the same structure.

As a first step, all possible alternatives are listed and a hierarchy of criteria is created, with respect to which the alternatives are evaluated. At the lowest level, there are measurable criteria for each alternative. With each ascending level, the criteria become combined

and more abstract, with the top level including the summary criteria that are believed to provide the final decision support. The criteria at each level are compared and scored from 1 to 9, with the opposing field always receiving the reciprocal ($1/x$), resulting in a matrix M . These values are commonly created from expert opinions. The largest Eigenvalue λ_{max} is used to evaluate the consistency of the matrix M through a Consistency Index CI (Equation (15)):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (15)$$

Here, n denotes the dimension of the matrix. The CI is divided by an empirical ratio R , yielding the Consistency Ratio CR , which must be below 0.1 for M to be deemed consistent [86]. The Eigenvector corresponding to the largest Eigenvalue represents the relative weight of each of the alternatives and is normalized such that the sum of the weights equals unity.

The bottom-most level contains metrics that characterize recorded values of each alternative. The value vectors from the lower level are collected as columns in the next higher level and matrix-multiplied with the Eigenvector to yield the preference of each alternative at the current level. This method is recursively applied in a post-order tree traversal scheme (Figure 4) until the upper-most level, which yields the final preference, is reached.

Algorithm AHP-calculation

Input: Nodes n_i
Input: Values $v_j \forall$ leaf nodes n_j
Input: Weights $w_k \forall n_i \notin n_j$
Output: Values for v_i for all nodes
Output: Relative Preferences $\lambda_k \forall n_i \notin n_j$
Output: Global Preference $p_k \forall n_i \notin n_j$

```

1: for all  $n_i$  do
2:   if  $v_i$  is populated then
3:      $p_i = v_i * \lambda_k$ 
4:     set parent  $v_{i-1} = p_i$ 
5:   else
6:      $\lambda_k \leftarrow \lambda_{max}$  of  $w_k$ 
7:   end if
8:   return  $p, n$ 
9: end for

```

Figure 4. The figure shows the calculation of an AHP. A tree structure must be defined before applying the process. The algorithm needs values for all leaf nodes and weights for all other nodes in the tree. It is a variant of post-order tree traversal where all leaf nodes get processed before parents. The parents collect the value vectors of all their children in a matrix and perform a matrix–vector multiplication with the relative preference Eigenvector λ to generate their own value vector.

3.5. Implementation

The AHP and all associated files were implemented as Python files and made available at https://github.com/Schlorch00/AHP_Paper (accessed on 18 December 2024). The software package contains an environment file for use with pip or conda, as well as a custom installable pip package for source files. The script folder contains command line scripts for processes defined in Figure 5. The package also contains example Excel sheets that can be used for creating proprietary weight matrices and value vectors for non-computer-scientists.

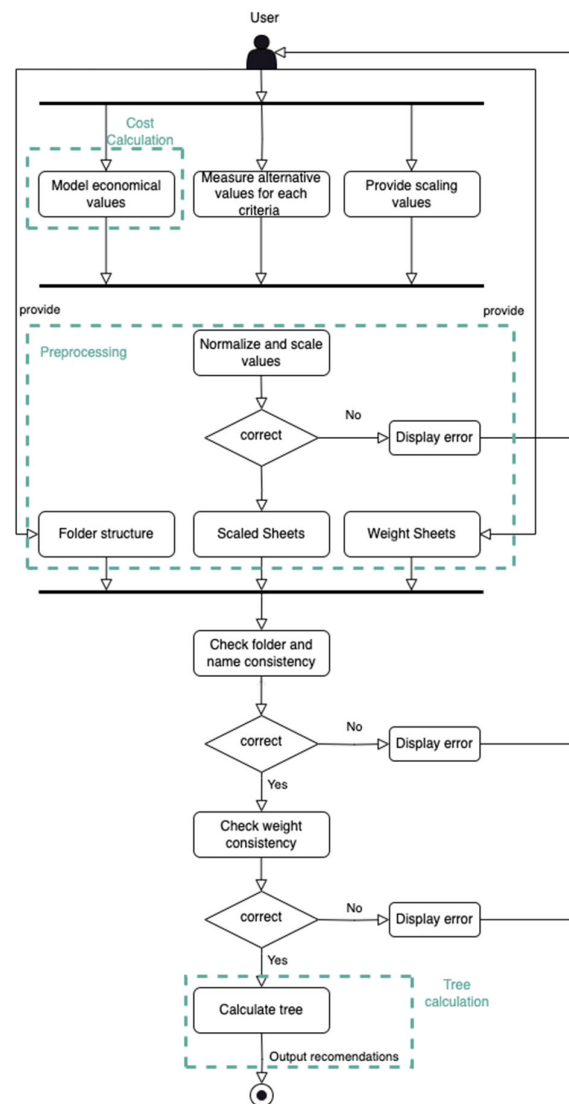


Figure 5. Data flow diagram between user, preprocessing, cost calculation, and tree calculation. Open rectangles define data structures mostly in the form of spreadsheets and circles denote processes that are executed. Cost calculation and preprocessing are supplied as standalone scripts while consistency checks are contained as part of the tree setup and calculation.

The AHP structure is implemented as a tree (Figure 3). Nodes can be created from weight or value matrices and added to the tree. A preparation step calculates all Eigenvectors, checks for consistency, and sets up hidden values before allowing for execution of tree calculation. The calculation is executed as a post-order traversal of a tree (Figure 4) and care should be taken when naming child nodes and rows and columns in spreadsheets as this may fail.

The user (Figure 5) can model the economic values based on the proposed cost calculation approach. Together with the measured data, like mechanical or ecological standards, and the option to set these data into proportion with the scaling values, the preprocessing steps can be executed. If structural and weighting consistency is given, the actual tree calculation with the AHP method can take place.

3.6. Preprocessing

Preprocessing of metrics is required to scale alternatives between 0 and 1. Helper scripts have been provided as part of the package. A Python script reads in spreadsheets wherein the second sheet is used to set options for scaling according to desired inputs. The

user is provided with the option of linearly scaling between the values (e.g., the lowest encountered value is 0, the highest 1), providing known boundaries (maximum or minimum), inverting the values, or a combination of all. Furthermore, the option for quadratic scaling is given, and this is used, for example, for process parameters, where deviation from an optimum value in both directions is problematic for the printing process and an ideal value and a maximum deviation are supplied. The detailed scaling options used for the calculation are presented in Supplementary Materials Tables S3–S21. The preprocessing scripts check consistency of values between 0 and 1 before writing to spreadsheet files, which should be checked by hand before being directly used as value files for the AHP.

3.7. Economic Factors

A script has been provided to supply the economical calculations presented in the methodology section's cost calculation for different materials. The script also provides the option of directly entering values in EUR/g instead of calculating them from the script if known. Two more scripts enable the linear combination of multiple materials, e.g., if supporting structures are printed from different materials to reduce costs. Economic factors are included in the comparison through an economical node at the highest level. These are calculated in four dimensions, which influence the economical decision about using alternative materials.

3.8. Weighting Process

To distinguish which factors are considered more important than others, the weighting process is necessary. These weights are later used to calculate the relative preference for each level through the eigenvectors shown in Figure 4. The weighting process is based on the pairwise comparison of the criteria at each level of the hierarchical tree. Saaty proposed a weighting classification ranging from 1 (equally important) to 9 (very important) when comparing two criteria [91]. This scheme is aligned to the weighting procedure of this work.

A complete overview of the pairwise comparison matrices is provided in Figure 6. The row criteria are favored against the column criteria in terms of the set value.

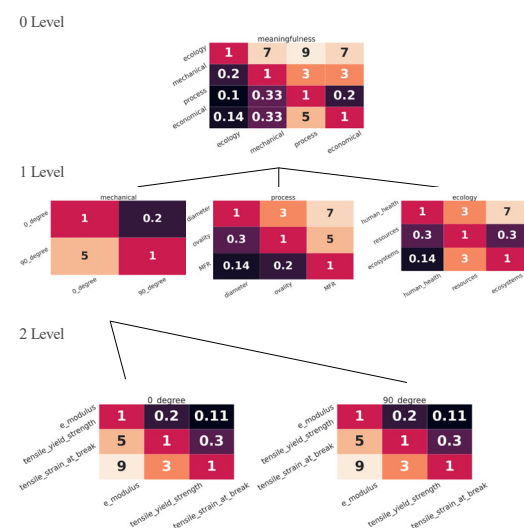


Figure 6. Pairwise comparison matrices of the implemented AHP method from level 0 to level 2 corresponding to the defined criteria at each level and a comparison score from 1 (equally important in comparison) to 9 (way more important in comparison).

3.8.1. High-Level Weighting (0th Level)

At the top level, the high-level criteria of mechanical, process-influencing, ecological, and economic parameters are weighted against each other. Due to increasing pressure of

environmental demands and legislations [95], e.g., by the 8th Environment Action Program (EAP) [96,97] or the Circular Economy Package [98] of the European Union (EU), as well as activities of the Regional Environmental Centre of Central Asia (CAREC) [99] and China [100], the ecological criterium is ranked highest. The increasing consumer awareness of sustainable products [101] further confirms this decision. Since the process-influencing parameters must be within a certain threshold in order to achieve feasibility in terms of manufacturing the parts, this is rated the worst. If there is no way to recycle a material, all other criteria are meaningless. The authors therefore take the recyclability of a material for granted. The mechanical parameters are ranked higher than the economic parameters based on following arguments: (1) subsidies for recycling and recycled material [102,103], as well as taxation of virgin or waste [104], can reduce the costs for material circularity or remanufacturing processes and (2) improvement of recycling processes and technologies [105,106] and optimized business and logistic models [107,108] can reduce the costs for material circularity or remanufacturing processes. Therefore, the goal of achieving similar performance properties (i.e., mechanical) between virgin and recycled materials is valued more highly.

3.8.2. Mechanical Performance Weighting (1st Level)

The performance properties in 0° direction to the layer printing direction are corresponding approximately to bulk properties of the material and normally outperform the properties in 90° direction. Nevertheless, the layer bonding between the filament strands is one of the most critical factors within the FFF-process. Therefore, the properties in the 90° direction are presumed as more important and ranked higher.

3.8.3. Process Performance Weighting (1st Level)

The investigated criteria addressing process-influencing parameters include the diameter, the ovality, and the MFR of corresponding filaments. The critical factor in terms of feasibility here is the diameter of the filament [88,109]. Ovality and MFR deviations are important properties for the quality and aesthetics of the print job [88] but are not as risky for the fulfillment of the print's completion. Since exceeding the diameter tolerances can lead to nozzle blockages or defective material extraction, the diameter criterion is rated highest, whereas a large deviation of the MFR compared to the status quo (virgin) [88] is rated lowest.

3.8.4. Ecological Performance Weighting (1st Level)

The ecological performance parameters result from the ReCipe Endpoint method performing the standardized LCA approach via ISO 14040/44 [83,84]. The endpoint criteria include human health, ecosystems, and resources, resulting from 17 medium-impact categories [34]. Since human health has an active influence on individuals and society, it comes first, followed by ecosystems, as their changes can affect us humans in the medium-to-long term. Since resources and resource use are also important, the impact of resource scarcity can potentially be reduced by people's adaptability and creativity in scientific innovation. Therefore, the parameters related to resources are ranked lowest.

3.8.5. Mechanical Performance 0- and 90-Degree Print Direction Weighting (2nd Level)

Based on the mechanical testing according to ISO 527 [85], Young's modulus, yield strength, and tensile strain at break are measured. The stress-strain behavior of a thermoplastic material can be simplified by elastic, plateau, and densification regimes [110]. Since the nonlinear material behavior until failure is the more interesting area for assessing changes in the micro- and meso-structure of a material, the ranking is established from highest to lowest value as follows: tensile strain at break, yield strength, and Young's Modulus.

4. Results

4.1. Extension of an MCDM Support Framework to Assess the Meaningfulness of Recycling

The comparison of materials regarding their performance classification demands a complex consideration of multiple domains (physical performance, processability, economic factors, ecological impact, etc.). As each of these fields allows in-depth research of its own, the quantification and qualification of materials or products in relation to these areas is often performed in isolation. In combination with the process complexity of recycling cycles, a comprehensive and quantitative comparison of virgin and recycled materials is limited.

In this work, a framework for evaluating and combining multiple domains is proposed. Four assessment domains—process feasibility, functional quality, sustainability, and economy—have been integrated and parameterized. The parametrization of the domains has followed measurable or/and calculated values according to well-known standards (ISO 527, ISO 1133, ISO 14044) [83–86] or measurement setups. The combination of these often-contradictory parameters enables a more comprehensive assessment of the question of whether recycling makes sense or not.

Apart from the fields evaluated and the chosen parameters and measurement methods, the proposed comparison is far from complete. Additional domains such as the logistical domain of the linear vs. the recycling process [111], the influence of material criticality [112], and trends of the plastic industry [113] will complement a more comprehensive investigation. Additional physical performance parameters (fatigue testing [114]), process-influencing parameters (shear thinning/thickening [115] and polymer shrinkage [116]), economic factors (ROI [117] or EoL-costs [118]), and ecological impacts (the water footprint [119]) are likely to increase the precision of the decision results. The flexible, tree-like structure is predestined to manipulate or add the configuration of the different levels.

Next to an implemented recycling scenario plus testing at a laboratory scale, an upscaled approach for industrial recycling has been calculated and integrated as an alternative for decision-making. The stepwise approach starting from domain identification, parametrization, and quantification toward the upscaling of values based on industry information has been proposed to accelerate decisions towards or against recycling. By utilizing the AHP method, one must mention that the addition or deletion of alternatives could lead to a phenomenon of rank reversal [120]. The implemented weighting method (pairwise comparison) is based on subjective expert judgment and yields some flexibility but also vagueness and uncertainty of data. The flexibility of weighting allows a quick adaption to different scenarios (change of legislation, subsidies for manufacturing processes, etc.) and various decision scenarios are possible to explore.

4.2. Integration of Cost Factors as Model Input

The proposed cost model delivers an input (leaf node) value for the economic parameter at level 1. The following example calculation demonstrates the various steps based on the measured data of the lab recycling process of the PLA filament. All cost positions (machine purchasing cost $P_{PLA_cost_lab}$, operating costs $O_{PLA_cost_lab}$, and labor cost $L_{PLA_cost_lab}$) included the three recycling steps of shredding, conditioning, and extrusion. The material costs M_i were neglected as no additional materials were added and 100% of the EOL virgin material was used. R relates to the amount of recycling material in g obtained through one recycling batch. The input values of the cost calculation are presented in Supplementary Materials Tables S1 and S2.

4.2.1. Machine Purchasing Cost

The total machine purchasing costs (Equation (16)) were split into the single costs of the shredder $P_{shredding}$, the extruder $P_{extrusion}$, and the vacuum oven for conditioning $P_{conditioning}$. The formulas used for calculation are shown in Section 3.3 in Equations (3) and (4).

$$P_{PLA_cost_lab} = P_{shredding} + P_{extrusion} + P_{conditioning} = \frac{P_{Purch_shredding} \cdot T_{Pro_shredding}}{0.95 \cdot 24 \cdot 365 \cdot Y_{life_shredding}} + \frac{P_{Purch_extrusion} \cdot T_{Pro_extrusion}}{0.95 \cdot 24 \cdot 365 \cdot Y_{life_extrusion}} + \frac{P_{Purch_conditioning} \cdot T_{Pro_conditioning}}{0.95 \cdot 24 \cdot 365 \cdot Y_{life_conditioning}} = \frac{3500 \cdot 0.0000571}{0.95 \cdot 24 \cdot 365 \cdot 6} + \frac{6000 \cdot 0.0008}{0.95 \cdot 24 \cdot 365 \cdot 6} + \frac{10000 \cdot 0.0027}{0.95 \cdot 24 \cdot 365 \cdot 8} = 0.0005101 \text{ EUR/R} \quad (16)$$

4.2.2. Operating Costs

The operating costs (Equation (17)) were following Equations (5) and (7) from Section 3.3. There were two options integrated for calculation in terms of the multiplication of the energy rate C_{energy} or the production rate C_O with the production time T_{Pro} . Based on the default value in the cost calculation.py script, C_{energy} was taken for the example calculation.

(default : E_{Pro} = production instead of T_{Pro} & C_{energy} = energy rate instead of C_O = production rate)

$$O_{PLA_cost_lab} = O_{Pro_shredding} + O_{Pro_extrusion} + O_{Pro_conditioning} = E_{Pro_shredding} \cdot xC_{energy} + E_{Pro_extrusion} \cdot C_{energy} + E_{Pro_conditioning} \cdot C_{energy} = 0.138 \cdot 0.207 + 0.417 \cdot 0.207 + 3.28 \cdot 0.207 = 0.79386 \text{ EUR/R} \quad (17)$$

4.2.3. Lab Costs

The labor cost (Equation (18)) contained the steps required for preprocessing, processing, and postprocessing for all three steps throughout the recycling process. The calculation was based on Equations (10) and (12) in Section 3.3.

$$L_{PLA_cost_lab} = L_{Pre_shredding} + L_{Pre_extrusion} + L_{Pre_conditioning} + L_{Pro_shredding} + L_{Pro_extrusion} + L_{Pro_conditioning} + L_{Post_shredding} + L_{Post_extrusion} + L_{Post_conditioning} = L_{Pre_shredding} \cdot xC_{labour} + L_{Pre_extrusion} \cdot xC_{labour} + L_{Pre_conditioning} \cdot xC_{labour} + L_{Pro_shredding} \cdot xC_{labour} + L_{Pro_extrusion} \cdot xC_{labour} + L_{Pro_conditioning} \cdot xC_{labour} = 0.083 \cdot 75.41 + 0.33 \cdot 75.41 + 0.05 \cdot 75.41 + 0.33 \cdot 75.41 + 0.083 \cdot 75.41 + 0.083 \cdot 75.41 = 72.318 \text{ EUR/R} \quad (18)$$

4.2.4. Overall Costs

The total cost position (Equation (19)) of the recycling process was yielded by Equations (1) and (2) listed in Section 3.3. The total cost and the amount of recycled material (for PLA: 936 g; see Supplementary Materials Table S23) were equivalent (Equation (20)) to one recycling batch R.

$$C_{PLA_cost_lab} = \sum_i^n P_{type_PLA_cost_lab} + \sum_i^n O_{type_PLA_cost_lab} + \sum_i^n L_{type_PLA_cost_lab} = 0.0005101 \text{ EUR/R} + 0.79386 \text{ EUR/R} + 72.318 \text{ EUR/R} = 73.112 \text{ EUR/R} \quad (19)$$

$$C_{EUR/g_PLA_cost_lab} = \frac{C_{PLA_cost_lab}}{\text{recycling_mass}_{PLA} \text{ per recycling cycle R}} = \frac{73.112 \text{ EUR/R}}{936 \text{ g/R}} = 0.0781 \text{ EUR/g} \quad (20)$$

The detailed calculation of the cost calculation script showed a difference of two to three orders of magnitude for labor and operating costs to operating or machine purchase costs.

Obviously, labor costs had the biggest impact on overall filament costs. From Table 4, it is clear that the total costs of all lab-recycled filaments surpassed those of the virgin counterparts. The work-intensive shredding process, e.g., constant refilling during and cleaning after the process, together with the high lab rate (net costs of 75.41 EUR for an

E13 researcher in Germany, TV-L), strongly influenced the overall costs. Greater laboratory efficiency (high throughput, less manual work, fewer interactions) was the main factor that led to the low overall cost of industrially recycled filaments.

Table 4. Calculated total costs (EUR/kg) based on the proposed cost calculation model of the investigated polymers (PLA, PP, and PP support) regarding their processing states (virgin, lab-recycled, and industrial-recycled). Virgin filament costs and values for recycling amount R are shown in Supplementary Materials Tables S22 and S23.

Polymer	Processing State	Total Costs [EUR/kg]
PLA	virgin	34.9
	lab-recycled	78.1
	industrial-recycled	6.7
PP	virgin	75.8
	lab-recycled	73.6
	industrial-recycled	4.0
PP Support	virgin	233.0
	lab-recycled	503.7
	industrial-recycled	26.0

4.3. Software Package

An open source Python software tool has been provided on GitHub that includes the AHP calculation, preprocessing and complementary tools with all calculations used in this paper (https://github.com/Schlorch00/AHP_Paper, accessed on 18 December 2024). A software tool has been developed that completes all calculations to enable a wider audience of researchers to use the method presented in this research. The software tool facilitates use by dividing the computation into the steps shown in Figure 5 via scripts that interact with intermediate output files and are executed via command line arguments.

The intermediate output files allow researchers to examine, verify, and modify values during the calculation process before moving on to the next steps, improving understanding and reproducibility. Command line arguments ensure that researchers do not have to reimplement code or make changes to complicated packages and can run the scripts from the command line after a simple two-step installation process.

The script running the full AHP calculation can be run from the command line or adapted for more detailed inspection. The value files generated by the preprocessing script should be placed in a directory structure representing the tree along with the weight spreadsheets at each level. A utility function allows the construction of the AHP tree from the root directory. In the subsequent steps inside the script, the tree is prepared and checked for consistency before calculation is executed. The final resulting tree can be inspected at each level by accessing the children or parents of each node and plotting or outputting values and preferences. An example directory has been provided in the repository.

Researchers can use the sample files provided to change naming and values according to their needs while ensuring compatibility with the software, minimizing the effort of using this package. The software's versatile structure allows it to be used for most multi-domain assessment tasks within and outside of multi-domain sustainability assessments.

4.4. Example Calculation Using 3d Printing as a Contemporary Use Case

Overall, three different scenarios (scenarios 1, 2, and 3) are presented to validate the approach. Scenario 1 considers two different materials (PLA and PP) applied on a simple cuboid geometry. Only one material type (PLA and PP) with its three alternatives (virgin, lab-recycled, ind-recycled) is considered. Scenario 2 investigates the main printing materials (PLA and PP) with their corresponding support filaments (PVA and PP support) applied on a complex impeller geometry. The third scenario compares both material types plus their support structure applied to the impeller geometry. The last example serves

as a potential example of multi-material mixing/comparison. For simplicity, the naming convention for the multi-material combinations (scenarios 2 and 3) is set to the actual printing material of the objects but includes the support material as well. The proposed values are following the hierarchical structure of Figure 3 with the leaf nodes (measured or calculated input values) excluded as no calculation is taken place. The leaf node values are presented in Tables 1–4. The calculated values propagated through the tree follow the calculation schema of Figure 4 with the final score at the final parent node at the top of the tree.

4.4.1. Scenario 1 (Simple Geometry, One Material, Comparison of Same Material Types)

Figure 7 shows the values of the MCDM approach of bio-based PLA applied on simple geometry. The high-level outcome tends towards the virgin material, followed by the recycling scenario at the industrial scale. Lab-based recycling is no option. Investigating the tree, the following values have to be clarified. The 0.00 value results from the scaling approach where the minimal outcome is set towards the minimal scaling value. In terms of ecological parameters, the virgin material outperforms the recycling options. The energy-demanding processes of the recycling cycle (even at the industrial scale) are not competitive at a simple mono-material geometry [89]. Additionally, mechanical and process data highlight the decreased material behavior after the recycling process for PLA [88]. Based on the weighting definition (see Figure 6), even potential cost savings through industrial scaling would not rectify the overall decision towards recycling. This outcome underlines the need for a multi-domain assessment and not just manifest recycling in general as the most sustainable solution.

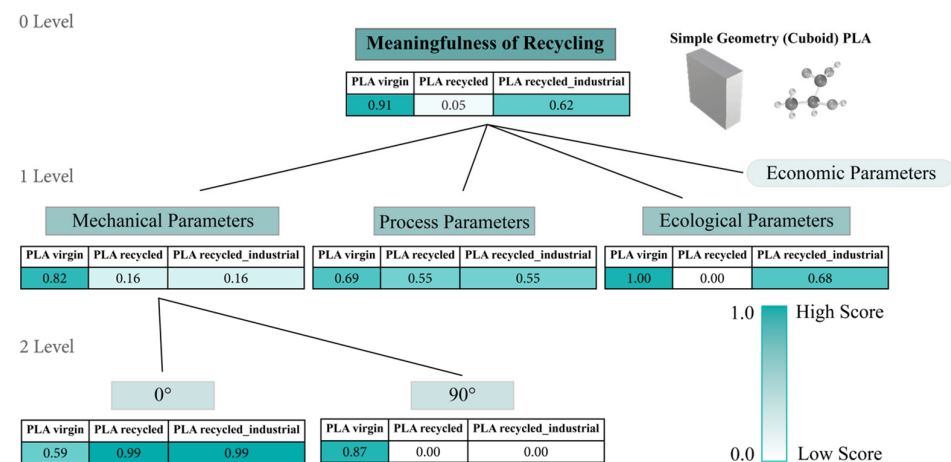


Figure 7. Eigenvalues of scenario 1 with PLA as the investigated material applied to a simple cuboid geometry.

The multi-criteria assessment of the recycling cycle addressing PP in comparison with the virgin material is demonstrated in Figure 8. Especially, the environmental potential of the industrial-scaled recycling process shows the efficiency of the recycling processes of common industry (see data in Supplementary Materials Table S2). The poor result of the lab-recycled version is the product of the scaling schema based on the definition of the minimal boundary (min–max normalization of just three values if no alternative min–max boundary is provided). The process and mechanical properties of the recycled material are competitive with the virgin PP [88] and yield a tendency toward the recycled material at an industrial scale. Without the logistic and sorting process, the cost calculation further proves the economic potential of the industrial recycling process at an industrial scale.

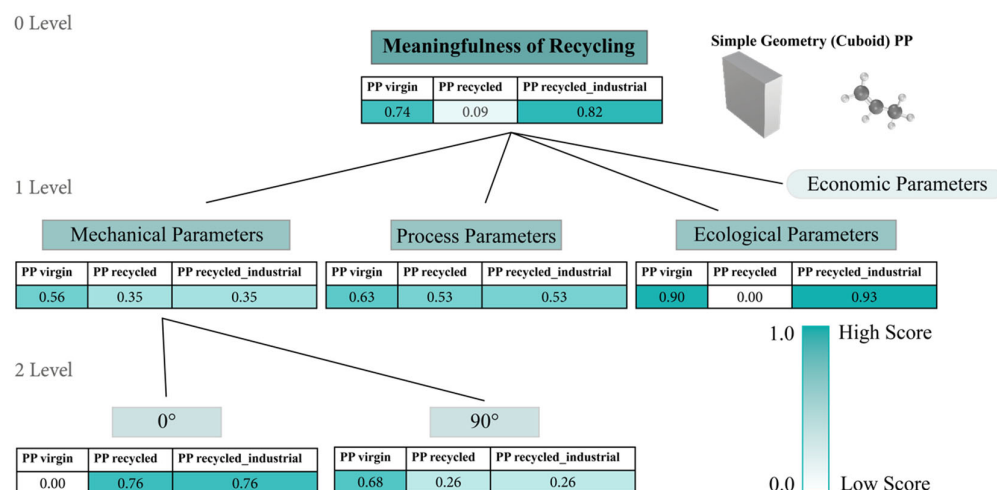


Figure 8. Eigenvalues of scenario 1 with PP as the investigated material applied to a simple cuboid geometry.

4.4.2. Scenario 2 (Complex Geometry, Two Materials, Comparison of Same Material Types)

The AHP performed on the complex impeller geometry with a combination of PLA and its corresponding support material PVA is visualized in Figure 9. In this case, only the PLA material is recycled as PVA material is a water-soluble support structure and is not reusable. The process, mechanical, and economic parameters are analogous to scenario 1, but the bigger amount of recyclable material regarding a more efficient industrial scaling favors an upscaled recycling process against the virgin and the lab-recycled PLA [89].

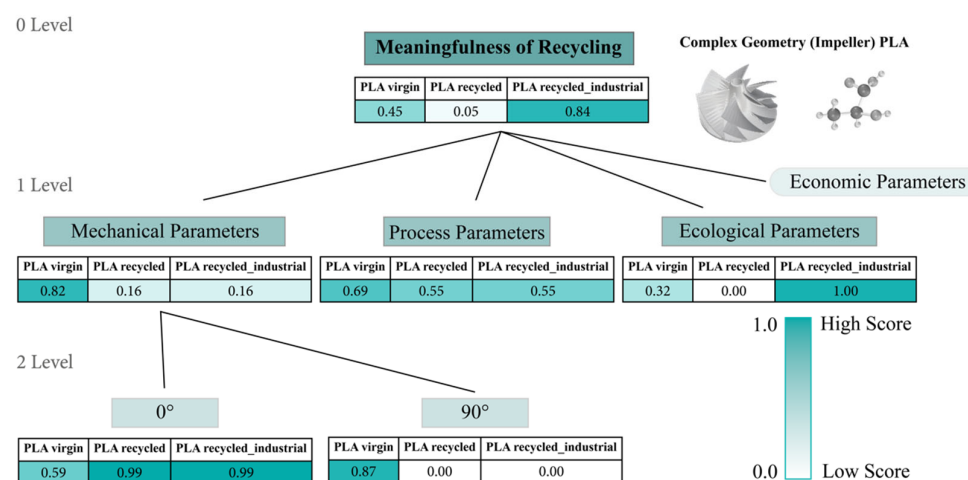


Figure 9. Eigenvalues of scenario 2 with PLA and PVA as the investigated materials applied to a complex impeller geometry.

Figure 10 highlights the meaningfulness of recycling towards the recycled PP based on industrial scaling. Equal values for process, mechanical, and economical parameters with the same weights applied as in the former scenarios are set for the corresponding input domains. Like scenario 2 with PLA, the ecological input shifts more towards the industrial-scaled, recycled PP caused by more efficient manufacturing processes [89]. Based on the favored weighting towards ecology and the higher mass of recyclable content, an improvement of the overall score can be achieved.

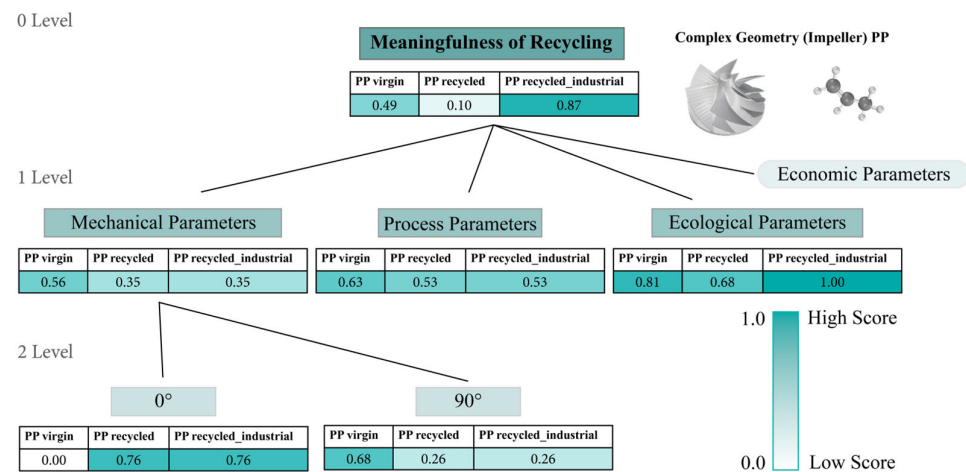


Figure 10. Eigenvalues of scenario 2 with PP and PP support as the investigated materials applied to a complex impeller geometry.

Contrary to the complex PLA structure, where only the PLA material is recyclable, both PP and the PP support structure can be reused in the recycling process. Other than PVA, the break-away PP support structure detaches from the printed object due to a thermomechanical debonding when a certain temperature is applied.

4.4.3. Scenario 3 (Complex Geometry, Two Materials, Comparison of Different Material Types)

To show-case the flexibility of the software tool, a combination of different materials (PLA and PP) with the complex geometry is performed and demonstrated in Figure 11. The same weighting schema was applied (Figure 6) and the scaling for mechanical values was set to the group maximum. Scaling options for process, ecological, and economical parameters were adapted from the previous scenarios. At the process level, the MFR value was eliminated as it was purely a material-specific value for the rheological properties and was not valuable for comparisons. The overall result sympathized with the recycled PP at an industrial scale. In general, all PP materials surpassed PLA materials due to the higher environmental impact of the PLA materials [89]. At the mechanical level, the weighting towards the plastic parameter tensile strain at break resulted in better performance, and even the elastic and elastoplastic parameters favored PLA (Table 1). Furthermore, the better performance of the two process parameters (Table 2) yielded a higher result for the PLA materials. Nevertheless, the higher weighted economic and ecological parameters (Tables 3 and 4) dominated the overall outcome, where especially the industrial-scaled, recycled PP outperformed its alternatives. The same scenario was simulated with two different weighting schemas at the highest level (0th level), and these are shown in Supplementary Materials Figures S1 and S2. Even with the variation towards two corner cases (mechanical parameters dominant and economical parameters dominant), the recycled PP impeller at the industrial scale was favored in terms of the meaningfulness of recycling. Additionally, the combination of PLA and PP material increased/changed the alternatives and highlighted the phenomena of rank reversal [120] (Figure 12), clearly visible through the decreased difference between the lab-recycled and industrial-recycled PP material compared to scenarios 1 and 2.

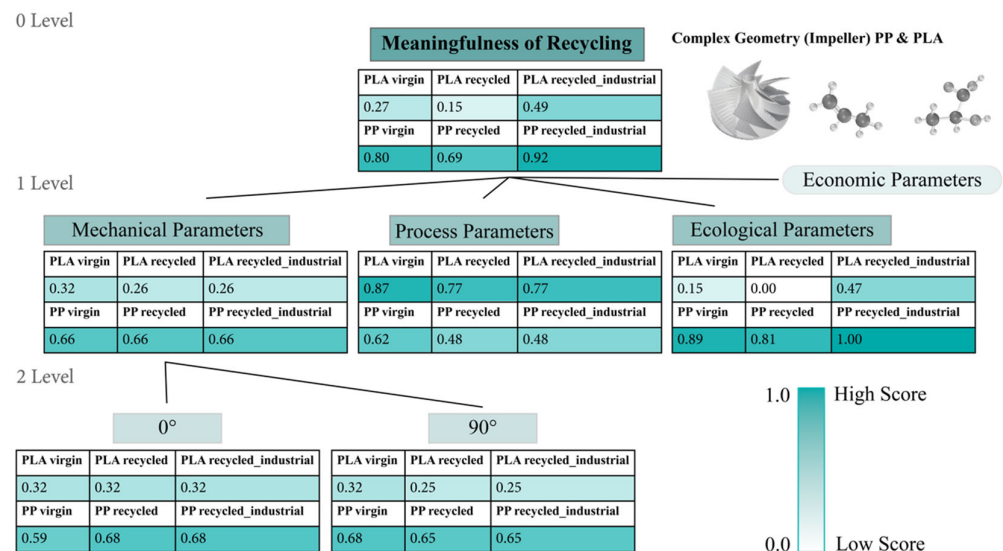


Figure 11. Eigenvalues of scenario 3 with PP and PP support and PLA and PVA as the investigated materials applied to a complex impeller geometry.

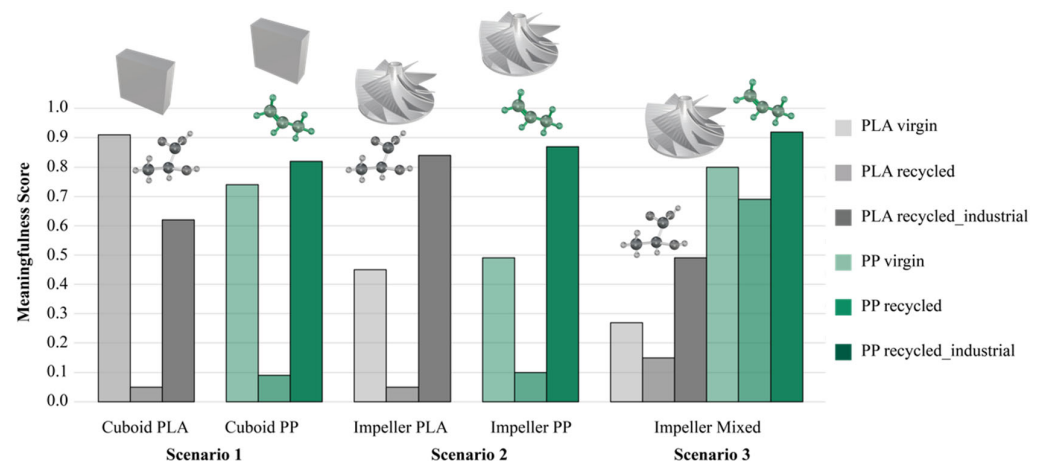


Figure 12. Overview of the investigated scenarios: (i) scenario 1 with simple cuboid geometry (PLA and PP); (ii) scenario 2 with complex impeller geometry (PLA and PP); (iii) scenario 3 with complex geometry and comparison of PLA and PP materials.

5. Discussion

An overview of the different scenarios is presented in Figure 12. Based on the proposed decision-making approach, the following statements can be testified [121–126]:

- Scenario 1's PLA shows that recycling cannot be generalized as automatically favored compared with a virgin manufacturing process. Therefore, a quantitative assessment with a verified and validated decision-making process is essential.
- Lab recycling in all scenarios performed worst. This was of minor concern as it proved the general approach and built the foundation for both scaling scenarios as well as a deep understanding of the single domains.
- Industrial recycling outperformed in most of the scenarios of the manufacturing process. This could be reasoned by an improvement in the efficiency of the upscaling process.
- Petroleum-based PP is meaningful for the recycling process. Next to comparable mechanical and process characteristics, an outperformance regarding the economic and ecological domain was visible.

Next to the presented outcomes, a scoping of the limitations is mandatory to address and accelerate further research. The methodological approach integrated four different and potential conflicting domains into a MCDM approach, more precisely the Analytic Hierarchical Process. The chosen domains highlighted the necessity to combine performance, manufacturing, ecology, and economy to tackle the question of the meaningfulness of recycling. The chosen parameters presented a possibility regarding implementing measurable and quantifiable values. Furthermore, it is highly recommended to extend and improve that framework with a variety of other parameters mentioned earlier [114–119] to state the results more precisely.

Similar reasoning can be applied to the scaling values applied for the input values. Nevertheless, a variation and adaption of scaling values is essential and up to further research. A scaling interval regarding the best and worst value from experiments, the literature, policy, or verified common sense will put the investigated values of each parameter into a better relation. This was demonstrated during the research, where, for example, the environmental values were just compared against each other and therefore resulted in values including 0 (lab-recycled) and 1 (ind-recycled). Combined with a strong weighting, the absolute score could have a bigger influence (see comparison: lab-recycled vs. industrial-recycled) as the actual distance between the input values.

A cost calculation based on [85] was extended and calculated for the corresponding recycling steps. This calculation seems appropriate if the remanufacturing process is embedded into the system of one facility or manufacturing side. The calculations represent a cradle-to-gate scenario without the cost impact of transport or sorting processes. The authors encourage further research to implement that in their cost calculation depending on the research question. Through the modular structure of the cost-calculation script, further processes (additional treatment process during the recycling, sorting, and logistics) can be easily implemented and configured to fulfill the demands of the user.

By comparing the total costs of the virgin with the recycled material, the key question addresses the meaningfulness for a company to build up a recycling system in their manufacturing circle. The extension of the cost calculation towards a commercialized product would include a more comprehensive consideration of in-detail product pricing and cost analysis including components like R&D costs, margins, marketing, operations and support, etc. [127].

The developed software module allows a quick set-up and calculation of the meaningfulness of addressing recycling. The software module is limited throughout the structure and calculation schema of the Analytic Hierarchical Process. More advanced and modern MCDM techniques like ML-based methods, HISA, or multi-graph and network-based methods are valid options to extend that framework. Nevertheless, this software is an established tool for an MCDM process. As a completely new method has not been proposed and the focus was set on the multi-domain integration of an application scenario, a comparison with other models seemed not necessary. Furthermore, the hierarchical structure of the AHP allowed a simple overview of the score development from root nodes to score nodes and identified bottlenecks. Moreover, the integration or extension of a variety of parameters at all levels of the hierarchical tree is completely flexible and up to the user, following the general set-up of the tree structure.

Considering the case scenario, a frequently asked question about the final score in most MCDM techniques relates to the subjectivity in criteria weighting [128]. The applied weighting method in this paper was adapted from the proposed scale of Saaty and had been well established [86,129]. A transparent explanation of the weighting values and a high-level variation of the weights proposed for scenario 3 would justify the main statements of the case study. Novel weighting approaches have been investigated by Ayan et al. [130].

Further extension of the proposed framework is expected to include various subjective or objective weighting methods [131]. Similar reasoning can be applied to the scaling values for the input values. Nevertheless, a variation and adaption of scaling values is essential and up to further research. Especially, the multi-material comparison show-cased in scenario 3 can vary distinctly depending on specific mechanical or process-influencing demands. The manipulation regarding the number of alternatives can lead to a phenomenon called ‘rank reversal’ [120]—shown in Figure 12, scenario 3—and needs to be considered by the investigator. On the other side, the robustness of the case study was demonstrated as neither the variation in the weights nor the extension of the alternatives changed the overall score preferring the industrial-recycled polypropylene.

6. Conclusions

The main objective of the presented research paper included the development of a methodological framework to quantitatively assess the meaningfulness of recycling. Next to the domains of performance, process, and ecology, a cost calculation approach for the recycling process has been suggested to integrate an economic domain. A software module has been developed to simplify the calculation and automate and scale the MCDM process. Several case studies based on bio-based (PLA) and petroleum-based (PP) FFF filaments have been investigated and interpreted. Based on the key contributions, the following closing remarks can be derived:

- A methodological framework of different domains (performance, process, ecology, economy) and implemented quantitative indicators (DIN ISO 527, DIN ISO 1133, DIN ISO 14044) and assessment options for further research has been presented.
- A cost calculation approach based on the performed recycling procedure has been set up and analytically calculated to verify the software results.
- The software module allows a flexible setup of parameters at each level, the error-controlled implementation of the weights, and the visualization of the weights and Eigenvalues at each level.
- The implementation has been verified and validated along a variety of case studies regarding the recycling process of petroleum-based and bio-based filaments.

In terms of the software implementation, the following benefits have been achieved:

- The abstract implementation of the software module is reproducible to any high-level, multi-criteria assessment task.
- The intermediate steps throughout the software execution allow the user to specify and control intermediate results (e.g., results after the cost calculation or preprocessing scripts).
- The whole software execution process can be executed throughout the command line.
- The authors have proposed the demonstrated visualization (also implemented in the final tree calculation script) of the AHP tree as a standard for the simple identification of hot spots and intermediate control of the values.

Based on the headline, regarding whether recycling is meaningful or not, the results regarding the various case studies can be summarized:

- The score of Scenario 1 (PLA and simple cuboid geometry) has shown that recycling, in general, should be assessed quantitatively with multiple domains to avoid the assumption that recycling—per se—is more meaningful than manufacturing virgin material.
- The other case studies have highlighted the improved overall score of the industrial-scaled, recycled material. This shows the necessity of a process- and cost-efficient recycling system to compete with linear manufacturing. Next to further investigations and research on the multi-attributive assessment of recycling, this can function as a

baseline to demonstrate the meaningfulness of recycling regarding certain types of thermoplastic AM filaments at a multi-attributive level.

- The petroleum-based filaments (PP and PP support) have demonstrated a high meaningfulness in terms of recycling. In particular, when comparing the complex geometry, the possibility to reimplement the actual material and the support material can benefit the decision towards recycling.
- The variation in weights and number of alternatives have demonstrated the results' robustness.

Overall, the authors have achieved a systematic and flexible assessment procedure for a multi-domain sustainability assessment at the material/product level. Nevertheless, considering sustainability and sustainable development as components of an open adaptive/complex system of high interdisciplinarity, further research regarding the upscaling of parameters and indicators and mathematical concepts to minimize subjectivity is mandatory to specify the quantitative results of sustainability assessment.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/recycling10010003/s1>, Table S1. Data acquisition for cost calculation of lab-recycled filaments based on measured and reviewed sources (Bay et al., 2023); Table S2. Data acquisition for cost calculation of ind-recycled filaments based on measured, reviewed, and provided sources from the industry (Bay et al., 2023); Table S3. Scaling schema for ecology data of scenario 1 (PLA & simple cuboid geometry); Table S4. Scaling schema for ecology data of scenario 1 (PP & simple cuboid geometry); Table S5. Scaling schema for ecology data of scenario 2 (PLA & complex impeller geometry); Table S6. Scaling schema for ecology data of scenario 2 (PP & complex impeller geometry); Table S7. Scaling schema for ecology data of scenario 3 (PLA vs. PP & complex impeller geometry); Table S8. Scaling schema for mechanical data of scenario 1,2 for 0°-direction (PLA); Table S9. Scaling schema for mechanical data of scenario 1,2. for 90°-direction (PLA); Table S10. Scaling schema for mechanical data of scenario 1,2 for 0°-direction (PP); Table S11. Scaling schema for mechanical data for scenario 1,2 for 90°direction (PP); Table S12. Scaling schema for mechanical data of scenario 3 for 0° direction (PLA vs. PP); Table S13. Scaling schema for mechanical data of scenario 3 for 90°-direction (PLA vs. PP); Table S14. Scaling schema for process data of scenario 1,2 (PLA); Table S15. Scaling schema for process data of scenario 1,2 (PP); Table S16. Scaling schema for process data of scenario 3 (PLA vs. PP); Table S17. Scaling schema for economic data of scenario 1 (PLA); Table S18. Scaling schema for economic data of scenario 1 (PP); Table S19. Scaling schema for economic data of scenario 2 (PLA); Table S20. Scaling schema for economic data of scenario 2 (PP); Table S21. Scaling schema for economic data of scenario 3 (PLA vs. PP); Table S22. Cost and mass of the commercial available filaments; Table S23. Recycled amount R of the investigated filaments (Nagengast et al., 2023; Bay et al., 2023); Figure S1. Scenario 3 with adapted high-level pairwise-comparison matrix towards preferred mechanical parameters; Figure S2. Scenario 3 with adapted high-level pairwise-comparison matrix towards preferred economic parameters. References [132–134] are cited in the Supplementary Materials.

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Abbreviations

Abbreviation	Name	Abbreviation	Name
PP	Polypropylene	MCDM	Multi-criteria decision-making
PLA	Poly Lactic Acid	AHP	Analytical Hierarchical Process
PVA	Polyvinylalcohol	LCA	Life Cycle Assessment
PVC	Polyvinylchloride	MFR	Melt Flow Rate
PE	Polyethylene	FFF	Fused Filament Fabrication
PS	Polystyrene	AM	Additive Manufacturing
DIN	German Institute for Standardization	CAREC	Regional Environmental Centre of Asia
ISO	International Organization for Standardization	CE	Circular Economy
C_{total}	Total cost of the whole recycling process	EOL	End of Life
C_i	Total Cost of each recycling step	EU	European Union
P_i	Purchase cost of utilized machine during each recycling step	M_i	Total material cost of each recycling step
O_i	Total operational cost of each recycling step	L_i	Total labor cost of each recycling step
PM_i	Total maintenance cost of each recycling step	T_{Prod}	Operation time of the machine
P_{Purch}	Machine purchase price	Y_{life}	Lifetime of the machine
O_{steps}	Operational cost of each step inside each recycling step	C_O	Operation rate
O_{Pre}	Operational cost of each preprocessing step	V	Volume of material
O_{Pro}	Operational cost of each processing step	C_m	Material rate
O_{Post}	Operational cost of each postprocessing step	ρ	Material Density
$O_{substeps}$	Operational cost of each step inside preprocessing, processing or postprocessing	m	Material mass
L_{steps}	Labor cost for each recycling step	L_{Pre}	Labor cost of each pre-processing step
T_L	Labor time	L_{Pro}	Labor cost of each processing step
C_L	Labor rate	L_{Post}	Labor cost of each post-processing step
$L_{substeps}$	Labor cost of each step inside preprocessing, processing, or postprocessing	$PM_{machine}$	Machine maintenance cost of each recycling step
$PM_{machine}$	Acquisition cost of each spare part	$Y_{machine_{life}}$	Extended life time of the machine
M	Matrix	CI	Consistency Index
λ_{max}	Largest Eigenvalue	CR	Consistency Ratio
TV-L (Public Sector Collective Agreement of the German states)	(German) Tarifvertrag der Länder	ASTM	American Society for Testing and Materials
ROI	Return of Investment	EAP	Environmental Action Program
R	Recycling batch	ML	Machine Learning

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