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Interim tandems of life cycle assessment methods and circularity indicators—elaboration for the circular bio-economy

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Introduction: The transition toward a circular economy (CE) is a key strategy for sustainable production and consumption, yet its contribution to sustainability depends on how it is assessed. Life Cycle Assessment (LCA) provides a robust framework for quantifying environmental impacts, but challenges arise when modeling circularity strategies such as recycling, recovery, and reuse. These include material quality degradation, allocation across successive uses, and capturing open-loop or cascading use patterns common in bio-based materials, which are modeled differently by different LCA methods. To address these challenges, this paper examines if and how circularity indicators (CIs) can complement LCA methods, with particular focus on the bioeconomy.
Methods: First, we review aspects and coverage of 48 identified circularity strategies for six prominent LCA methods—Product Environmental Footprint (PEF), EN 15804, Allocation at the Point of Substitution (APOS), and Consequential LCA (CLCA), and two system expansion approaches—alongside three stand-alone indicators: the Material Circularity Indicator (MCI), Circular Transition Indicators (CTI), and ISO 59020:2024. Using natural fiber insulation as a case study, we demonstrate the strengths and limitations of different LCA approaches.
Results and discussion: Results show that coverage of the 48 circularity strategies varies substantially among these LCA methods (13–42 covered) and CIs (9–22 covered). CLCA addresses the most circularity strategies (42). There are only five circularity strategies that are not covered by LCA, including those with socio-economic implications, which an improved life-cycle sustainability assessment framework could eventually address. In those five cases, the CIs CTI, and ISO 59020:2024 may be applied as a complement to LCA on an ad interim basis. A framework is proposed to select combined sets of LCA methods and CIs for specific goals and scopes.

KEYWORDS
allocation, bio-economy, circularity, circularity indicators, LCA standards, life cycle assessment, product environmental footprint guide, recycling

1 Introduction

The transition toward a circular economy (CE) is increasingly recognized as a key strategy for achieving more sustainable production and consumption systems. A circular economy is an "economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining, or adding to their value.[1]" (ISO, 2024a). By aiming to minimize waste, retain the value of materials, and reduce reliance on virgin resources, circularity ["degree of alignment with the principles of a circular economy" (ISO, 2024b)], has become a guiding principle in policy and industrial innovation (European Commission, 2018a). Yet, while circularity is often promoted as a sustainable solution, its actual sustainability, in terms of its contribution to environmental, economic, and social goals, depends, among other things, on how it is implemented and evaluated.

Circularity frameworks have been developed, such as the 9R framework, in which the circularity strategies refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose, recycle, and recover are ordered from high circularity (refuse) to low circularity (recover) (Potting et al., 2017; Kirchherr et al., 2017). This hierarchy of circularity strategies can be considered as a "rule of thumb" in identifying the strategy with presumably higher to lower environmental benefits (Potting et al., 2017). However, as Potting et al., also state, there are exceptions to this rule that can be identified through quantitative assessments. Furthermore, such a framework does not consider performance characteristics, such as recycling rates, the quality of recycled materials, and displacement rates of primary material, which, however, influence the environmental performance of circular systems (Geyer et al., 2016; Roosen et al., 2023).

Life Cycle Assessment (LCA) provides a robust framework for quantifying the environmental impacts of products and systems across their life cycles (i.e., including the extraction of raw materials, manufacturing, distribution, use, and end-of-life treatment) (ISO, 2006a), and can be applied to circular products. However, integrating circular strategies, such as recycling, recovery, or reuse, into LCA remains challenging due to the complexity of material quality degradation over time and the need to allocate the impacts of primary and secondary material production across successive product uses, particularly open-loop circularity. Current LCA guidelines—such as the EU's Product Environmental Footprint (PEF) (European Commission, 2020) and its Circular Footprint Formula (CFF)—offer some mechanisms to account for recycling and reuse, but critical gaps remain, particularly for bio-based materials with complex cascading use patterns. The CFF allows for the allocation of burdens and benefits of recycling between the upstream and downstream adjacent lifecycles in the LCA framework. However, like many other approaches, the PEF guide and CFF do not allow considering the burdens and benefits over multiple (finite) open-loop or cascading loops beyond adjacent loops (Schaubroeck et al., 2021a), whereas cascading is especially prominent for bio-based materials (e.g., for wood-based products).

Moreover, aspects such as the longevity of products and the quality of recycled materials after end of life (EoL), which are essential to achieving a more circular economy, are not commonly directly quantified in LCAs and are thus generally not communicated as results.

Circularity indicators (CIs) such as the Material Circularity Indicator (MCI) (Goddin et al., 2019), Product Circularity Indicator (PCI) (Bracquené et al., 2020), and Longevity Indicator (Franklin-Johnson et al., 2016; Figge et al., 2018) have emerged as stand-alone tools to reflect specific attributes of circularity—e.g., product lifespan, end-of-life material quality, and number of use cycles—that are commonly not fully captured in conventional LCA metrics. These indicators can offer more accessible and targeted insights, especially where LCA data are limited or modeling assumptions introduce significant uncertainty. However, circularity indicators may give the impression that circularity is an end in itself, while it should instead be considered a potential lever toward more sustainable systems [as quantified through a holistic and integrated Life Cycle Sustainability Assessment (LCSA)] (Bachmann et al., 2021; Walzberg et al., 2021).

Both the ORIENTING project (Bachmann et al., 2021; Pihkola et al., 2022a), and the circularity framework of Luthin et al. (2023), and by extension literature in general as reviewed by Kumar et al. (2025), advocate to quantify the circular performance of a product system with given indicators, and to report this performance as part of an LCSA, independently from the three sustainability pillars (environmental, social, and economic). However, these works do not provide a comprehensive overview of the implications of circular processes for LCA studies, as they must apply allocation procedures. Allocation procedures, in this case among different uses of products or materials across circular loops, are goal-and-scope dependent (Ekvall and Tillman, 1997; Schrijvers et al., 2020a; Schaubroeck et al., 2021a). This means that no universal LCA approach and matching CI can be recommended for a holistic understanding of the sustainability of a circular product system. More guidance is needed to link several modeling options for loops in a CE over time with the various goals and scopes represented by different LCA methods.

This paper addresses the complementarity and integration of circularity indicators with LCA and guides modeling circular product systems, with a particular focus on the bioeconomy. The circular bioeconomy has been brought forward as a potential sustainable path forward for society, with a need to apply and further research LCA methods and circularity indicators in this context (Tan and Lamers, 2021). Building on the methodological challenges identified in recent projects and the aforementioned literature, the four objectives of our paper are:

1. Demonstrate various LCA approaches to model circularity strategies, including recycling, reuse, and cascading bio-based material use.
2. Highlight the limitations of current methods and discuss potential solutions.
3. Offer structured guidance for selecting the most appropriate modeling method based on the goal and scope definition of the LCA study.

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[1] In the definition of ISO 59020 is mentioned: "while contributing to sustainable development". Yet, this was removed as it is not explicit in the term and potentially misleading as circular systems might not necessarily be sustainable. It is better to speak of a "sustainable circular economy" when wanting to cover both sustainability and circularity.

4. Assess the complementarity between LCA and circularity indicators, clarifying which aspects of circular performance are best captured by each approach, and crystallizing this into a general combined approach

By bringing together LCA approaches and circularity indicators in a consistent framework, this paper aims to support practitioners and decision-makers in making informed modeling choices, ultimately improving the evaluation and communication of circularity strategies within sustainability assessments.

2 Materials and methods

The section presents the selected "materials" (i.e., modeling frameworks) alongside the applied methodology.

2.1 Terminology of key concepts

To provide clarity, we first explain the terminology used. A starting point of this terminology is our interpretation of the definitions presented in ISO 14044 (ISO, 2006b). The key element of the formulation of a product system and the life cycle is the functional unit (FU) ["quantified performance of a product system for use as a reference unit" (ISO, 2006b)]. The functional unit is (one of) the output(s) of a product system ["collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product." (ISO, 2006b)]. The product system refers to the life cycle of *a* product, which we understand as the reference flow ["measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit" (ISO, 2006b)]. The life cycle of this reference flow represents the "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal." (ISO, 2006b). Elsewhere in ISO 14044, we find that "LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)" (ISO, 2006b). This sentence implies that the "end-of-life treatment" and the "final disposal" of a product are two separate stages, and a life cycle is modeled up to the final disposal. However, in practice and following LCA guidelines (among which the PEF Guide), a product's life cycle is generally modeled up to end-of-life treatment after a first use cycle, which may be recycling, reuse, or energy recovery (European Commission, 2018b). Therefore, in this paper, staying close to current LCA practice, we consider a product's life cycle up to (first) end-of-life treatment, where we interpret "end of life" as the "stage which a product reaches once it ceases to be used for its intended use." (Schrijvers et al., 2021a).

If the product under study (the reference flow) reaches its EoL, it may still be possible to use this product to fulfill an additional function that goes beyond the function that was defined by the functional unit. If this additional function becomes accessible after the end-of-life treatment stage, we say that the product can be used in a subsequent life cycle, or in a subsequent *loop*, as illustrated in Figure 1. The product flow entering a new loop can be considered as a *co-product* of the product system of the reference flow. In this paper, we call the life cycle that makes such a co-product available at the EoL the "preceding life cycle/loop", and the life cycle that uses this co-product as an input in its product system the "subsequent life cycle/loop". In the same vein, we call historical loops "upstream life cycles" and future loops "downstream life cycles".

2.2 Selection of LCA methods to model circularity strategies

To demonstrate how to model circularity strategies via LCA approaches (Objective 1), and highlight their limitations and discuss potential solutions (Objective 2), we selected the following LCA methods:

- the Product Environmental Footprint (PEF) Guide (European Commission, 2021),
- EN 15804+A2:2019 (CEN, 2012; AFNOR, 2022),
- Allocation at the Point of Substitution (APOS) (Schrijvers et al., 2021a),
- Consequential LCA (CLCA) as described by Weidema (2003); Weidema et al. (2009, 2013); Schrijvers et al. (2020b)
- System expansion from the recycling/valorization perspective (Schrijvers et al., 2020a), and
- System expansion from a multi-life cycle perspective (Schaubroeck et al., 2021a).

These methods were selected based on their prominence and/or scientific consistency. Furthermore, it was aimed to include a selection of LCA methods that cover a variety of LCA goals, as further detailed in the next section. These selected methods are further explained in the respective results sections and in the SI. For each of these LCA methods, it is demonstrated how system boundaries are applied and how this affects the allocation of impacts among different life cycles.

2.3 Goal-and-scope dependency of LCA models

To formulate guidance for selecting among modeling methods during an LCA (Objective 3), we acknowledge that method selection depends on the LCA's goal and scope. When a product system provides, besides the functional unit, additional functions or co-products as well, this product system is multifunctional, and an allocation procedure needs to be followed to identify the inputs and outputs that belong to each product system (Ekvall and Finnveden, 2001; Guinée et al., 2004; ISO, 2006b). In this work, we focus mainly on selecting the most appropriate methodology to address multifunctionality in circular processes within LCA. Like any other methodological choice, the modeling of multifunctional processes should primarily align with the study's

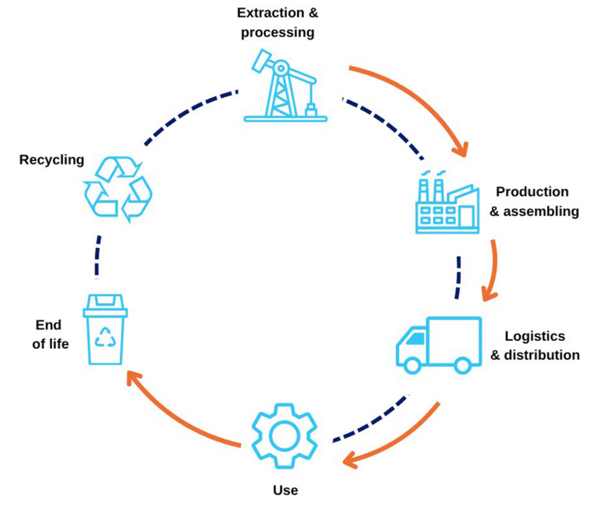

FIGURE 1
Depiction of a product's life cycle as a "loop" (WeLOOP, 2025).

goal.[2] Different goal aspects should be specified. According to ISO 14044, the goal shall cover: "the intended application; reasons for carrying out the study; intended audience; whether it is for a comparative assertion intended to be disclosed to the public." (ISO, 2006b). Schrijvers et al. (2020a) identified different "archetypes" of goal and scope definitions, all asking for a specific allocation procedure. The archetypes differ in the application of a process-oriented or product-oriented approach (related to the reason for conducting the study) and an attributional or consequential LCA (from the perspective of the LCA practitioner and the intended audience).

2.3.1 Product-oriented and process-oriented LCA

The first goal aspect is the implicit object of study. Here, we want to make a distinction between products (or the demand for them) and processes/systems as the object of study (Schrijvers et al., 2020a):

- **Product-oriented LCA:** Many studies have the objective to assess the footprint of a specific product, for example, for a comparison with alternative products, or for the establishment of an inventory, to be used in further downstream LCA studies. Given a focus on products (or the demands they entail), there is a clear need to address multifunctionality issues, particularly in waste valorization in the context of CE. Multifunctional processes can be modeled using partitioning, substitution, or the cut-off approach, as further explained in the SI.
- **Process-oriented LCA:** In several contexts, the LCA study is focused on the performance of a process, or a collection of processes. For example, the question can be posed whether recycling is better than incineration and primary production, or whether one process is "greener" than another. Here, it is less important to understand how the process's impacts are distributed across different product systems. For a focus on a process or a chain of multiple processes (of which a chain of multiple life cycles is a variant), one can apply system expansion, specifically functional unit expansion, in which all functional flows that are provided by the process(es) are considered in the functional unit.

2.3.2 Attributional and consequential LCA

The perspective of the LCA refers to the scope of impacts of interest to the LCA practitioner and the intended audience. Two main impact scopes are generally distinguished: attributional and consequential impacts:

- **Attributional LCA** "attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle). [...] The system analyzed ideally contains processes that are directly linked by (physical, energy, and service) flows to the unit process that supplies the Functional Unit (FU) or reference flow. [...] In theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide." (Sonnemann and Vigon, 2011). The UNEP-SETAC Shonan guidelines (Sonnemann and Vigon, 2011) were cited as the reference for definitions, according to the scientific selection procedure of Schaubroeck et al. (2021b). Attributional LCAs can be considered as "normative", as the linking of unit processes to the systems is based on a normative rule (Sonnemann and Vigon, 2011). Attributional product-oriented LCAs generally model multifunctional processes via partitioning (see also the SI) (Sonnemann and Vigon, 2011; Schrijvers et al., 2020a; Schaubroeck et al., 2022).
- **Consequential LCA** "attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product). [...] In theory, the systems analyzed in these LCAs are made up only of processes that are actually affected by the decision, that is, that change their output due to a signal they receive from a cause-and-effect chain whose origin is a particular decision." (Sonnemann and Vigon, 2011). In a consequential product-oriented LCA, multifunctionality is generally modeled by substitution (see also the SI) (Sonnemann and Vigon, 2011; Schrijvers et al., 2020a; Schaubroeck et al., 2022).

2.4 Identifying the complementarity of methods

To reach Objective 4 (assessing the complementarity of LCA and circularity indicators), "circularity attributes" are extracted from the LCA methods presented in the previous section. In this

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[2] In this context, we take into consideration the advice of Schaubroeck et al. (2022) given the inconsistencies in the ISO 14040-14044 standards. This advice points out to fully align multifunctionality choices with the goal and scope, and considers an open definition of the system as a whole, the product system.

article, circularity attributes refer to aspects of circularity that can be quantified or qualitatively assessed (e.g., a product's recycled content). The circularity attributes are identified by observing the allocation formulas, implicitly or explicitly used to calculate the Life Cycle Inventory and, subsequently, the environmental impact for each LCA method. Examples of these formulas can be found in Schrijvers et al. (2016a, 2020b). Each parameter in these formulas influences the final result of the impact assessment, and is therefore identified as a "circularity attribute". Each circularity attribute is then linked to a "circularity strategy". This circularity strategy refers to the action that aims to change the value of this attribute. For example, if the "recycled content" is a circularity attribute, "increasing the recycled content" would be the associated circularity strategy. Through this approach, the formulation of identified circularity strategies is more detailed and precise than circularity strategies formulated in other frameworks, such as the 9R framework, which treats "recycling" as a single strategy. This increased level of detail enables the identification of additional levers to reduce impact.

For each LCA method, an overview of the circularity attributes and the associated circularity strategies it covers, is provided. When a circularity attribute is "covered", it means that the implementation of a circularity strategy, which results in a change in the value of the associated circularity attribute, will result in a change in the assessment result when the method is applied. The list of circularity attributes from LCA methods is complemented by circularity attributes included in stand-alone circularity indicators and frameworks, as introduced in the next section. The identified circularity attributes are listed in Table 1 and, in more detail, in Supplementary Table 5. This list provides an overview of circularity attributes covered by at least one method. The circularity strategies collected in this paper are matched with the 10 R's of the 9R framework in Supplementary Table 5, to evaluate the extent of the framework's coverage. Each LCA method and circularity indicator is compared to this list of circularity strategies. Based on this, the comprehensiveness of the assessment method to assess a circularity strategy is evaluated, and potential complementary assessment methods are identified.

2.5 Selection of stand-alone circularity indicators

Circularity Indicators are measuring methods to assess the progress toward increased circularity at a product level, considering different circularity strategies (Bracquené et al., 2020). Such metrics support decision-making in, e.g., product design, material selection, tracking of Key Performance Indicators, or investment choices, and can be used to support discussions on how circularity impacts objectives, such as more viable business models, lower business risk, or improved social equity (Goddin et al., 2019).

The following circularity indicators and frameworks are evaluated for Objective 4, based on their broad recognition and their recommended use by the ORIENTING project (Bachmann et al., 2021; Pihkola et al., 2022). The ORIENTING project, a large Horizon Europe project with many stakeholders and partners involved, recommends using circularity indicators as a complement

TABLE 1 Circularity attributes covered by evaluated LCA methods and circularity indicators.

#	Circularity attribute
1	Recycled content
2	Reuse rate (in closed loop)
3	Renewable material content
4	End-of-life recycling rate
5	End-of-life energy recovery rate
6	The efficiency of the energy recovery process
7	Energy content of material
8	Efficiency of the recycling process at the EoL
9	Efficiency of the recycling process for the recycled content
10	Fraction of the product going to component reuse
11	Average number of cycles of a product or material for the defined use phase relative to an industry average
12	Mass of unrecoverable waste generated during the recycling process at EoL
13	Mass of unrecoverable waste generated during the recycling process for the recycled content
14	Reused content
15	Per cent of water demand that is derived from circular sources
16	Share of water consumed in process and operations that leaves the infrastructure for reuse by another organization or it is returned to the water source with the same/better quality
17	Share of energy consumed that is renewable energy
18	Quality degradation of recycled material
19	Impacts of the recycling process for the recycled content
20	Impacts of the recycling process at the EoL
21	Impacts of the consumed primary raw material
22	Impacts of the energy recovery process
23	Fraction of the product being collected to go into a composting process
24	Fraction of biological materials used which originate from Sustained Production
25	Fraction of the product being collected for recycling at EoL
26	Number of times a product is hired (multiple consumers during its use phase)
27	Mass of unrecoverable waste of product going into landfill, waste to energy
28	On-site water circulation (reuse and recycle) number of times the company uses the average drop of water onsite before it leaves the facility as outflow
29	Refurbishing rate
30	Remanufacturing rate
31	Potential uses of a produced recycled material (considering functionality and quality requirements)
32	Impacts of waste disposal without energy/raw material recovery
33	Impacts of the substituted production of primary raw materials
34	Multiple recycling loops in cascades
35	Level of demand or supply of a consumed recycled material

(Continued)

TABLE 1 (Continued)

#	Circularity attribute
36	Level of demand or supply of a produced recycled material
37	Level of demand or supply of produced recovered energy
38	Impacts of the substituted energy source
39	Level of demand or supply of consumed recovered energy
40	Downstream effects of recycling in the subsequent life cycle, beyond the substitution of primary raw materials (e.g., differences in transport, use and EoL)
41	Fraction of the product comprising biological materials from Sustained Production going to energy recovery
42	Average lifetime of a product or material relative to an industry average
43	Actual recovery rate relative to the theoretical recovery potential
44	Impacts of a substituted waste treatment process
45	Impacts of a substituted valorization process
46	Percentage of the total material/product which is considered to be a critical raw material
47	Material productivity (ratio of revenue generated by total mass of all linear resource inflows)
48	Resource intensity index (ratio of the increase in resource consumption to the increase of gross domestic product (GDP) over a period of time)

Additional notes and corresponding circularity strategies are provided in Supplementary Table 5.

to LCSA to “unveil and inform on potential trade-offs of circularity systems vs. environmental priorities in a consistent and visually expressive way.” (Bachmann et al., 2021).

- Material Circularity Indicator (MCI): The MCI evaluates how effectively a product reduces linear resource use and enhances restorative material flows. It considers virgin material input, unrecoverable waste, and a utility factor (product lifespan and usage intensity relative to industry norms). These inputs generate a score from 0 to 1, reflecting the product’s circularity (Goddin et al., 2019). The ORIENTING project recommends the MCI for the assessment of circularity at an advanced level, due to the consideration of information on the Bill of Materials, use, and EoL of materials and products (Pihkola et al., 2022).

- Circular Transition Indicators (CTI): Building on circular economy principles, the CTI provides a broader, company-level assessment. It includes material flows, water use, renewable energy, and business value. Unlike the MCI, the CTI does not yield a single score but uses a scorecard approach that accommodates estimates and assumptions (WBCSD, 2023). For an assessment at an intermediate level, the ORIENTING project recommends one of the indicators of the CTI (% Circularity), to avoid overlap with an LC(S)A (Pihkola et al., 2022).

- ISO 59020:2024: This international standard formalizes circularity assessment at the organizational level through standardized KPIs, structured methodologies, and rigorous data collection and reporting aligned with global guidelines (ISO, 2024a). This framework is included due to its recent publication.

2.6 Natural fiber insulation as illustrative case study

In the following sections, different approaches to model circularity situations in LCA are introduced. To highlight the differences between the methods, they are applied to an illustrative case study of insulation based on natural fibers. The application of the methods to the case study is conceptual, i.e., it is described in qualitative terms. In this illustrative case, it is assumed that the cellulose is extracted from end-of-life newspapers. Furthermore, the following realistic end-of-life scenarios for cellulose insulation could be envisaged:

1. Landfilling of non-hazardous materials.
2. Incineration with energy recovery.
3. Fibers are recycled to produce Solid Recovered Fuels (SRF).
4. Recovered fibers are used as stabilizing agents in asphalt.
5. Boron-impregnated fibers are pyrolyzed to produce biochar for the production of plant fertilizer (boron as a nutrient).
6. Recovered fibers are either directly reused or processed into the production line and recycled as insulation.

Process flow charts reflecting these end-of-life scenarios are presented in Supplementary Figure 2. In the results section, we refer to the life cycle of the first use of natural fiber insulation as the “preceding loop”. The valorized material or energy from end-of-life cellulose insulation is used in a “subsequent loop”.

3 Results

3.1 Assessment of LCA methods to model circular product systems

This section presents various LCA approaches for modeling circular product systems. Supplementary Table 1 presents example research questions and functional units that are coherent with the modeling methods. The system boundaries of each method are illustrated for the various end-of-life scenarios of cellulose insulation in the Supplementary Information, and the resulting impact and benefit assignments are discussed in the following sections. The circularity attributes and corresponding circularity strategies represented by each method are listed in Supplementary Table 5. For all scenarios, it was assumed that the cellulose used for insulation was supplied from end-of-life newspapers.

3.1.1 Product environmental footprint guide

Within the PEF Guide, the environmental footprint is assessed for a single product life cycle. Impacts of the end-of-life treatment of waste and benefits of waste valorization are shared between the supplier of the waste and the user of the valorized material, following the CFF (European Commission, 2021). A detailed presentation of the CFF is provided in the SI. The limitations of the PEF Guide are summarized in Table 2.

3.1.1.1 Allocation of impacts to the preceding loop of cellulose insulation

All scenarios: The end-of-life newspapers used as a source of cellulose are a secondary raw material. Therefore, the term referring to the recycled content (R1) in the CFF is applied to all scenarios. According to Part C of Annex II of the PEF Guide, the recycled content of cellulose-based thermal insulation material may be considered to be 100%, and a value of $A = 0.5$ shall be applied. Consequently, the recycling process for cellulose production from EoL newspapers is modeled for 50% of the total cellulose used. A primary production process models the remaining share of consumed cellulose. This may refer to the primary production of cellulose or another primary raw material that can be used in the same application. The selection of the primary production process may be specified in an applicable PEFCR document. If there are quality differences between recycled cellulose and the primary alternative, the primary production process is modeled for a corresponding lower (or higher) flow of raw materials.

Incineration/production of SRF: The two scenarios that allow for energy recovery (incineration and production of solid recovered fuels) model the valorized waste flow as "R3". As the value for B is set to 0 by default, the incineration process and the production processes of the fuels, as well as the substituted production of electricity and heat, are modeled at 100%. There is no explicit guidance within the PEF Guide to identify substituted production processes for heat and electricity.

Recycling as stabilizing agents in asphalt: The material-specific value $A = 0.5$ for cellulose insulation is applied to recycling insulation at the EoL. This means that the flow of EoL cellulose is only 50% modeled through further processing into stabilizing additives, and the substitution of primary additives is only 50% modeled. The specific primary additive that is substituted and reflected by $E * v$ is not defined in the PEF Guide, but may be specified in a PEFCR. The quantity of primary additives substituted is determined by "how well" they displace one another. The remaining 50% of the flow of EoL cellulose insulation is modeled by the "cut-off" principle, i.e., no further processing is modeled within the boundaries of the first life cycle.

Recycling into biochar for use as fertilizer: The use of biochar as fertilizer may be assimilated to "composting". According to the PEF Guide, for composting, a value of $A = 0.5$ shall be applied. This means that the flow of EoL cellulose is modeled only for 50% through further processing into biochar, and the substitution of Borax is modeled only for 50%. The quantity of Borax that is substituted shall reflect "how well" biochar may replace Borax, e.g., based on the boron content. The substitution of Borax reduces Borax leaching during the fertilizer application phase and increases naphthalene leaching. This downstream effect is not included in the CFF. The remaining 50% of the flow of EoL cellulose insulation is modeled by the "cut-off" approach, i.e., no further processing is included within the boundaries of the first life cycle.

Reuse as insulation: Reuse for the same functionality extends the product's lifetime. Each use cycle is accountable for impacts related to use and preparation for reuse. The impacts associated with the consumption of (secondary) raw materials and the final end-of-life treatment of the insulation material are divided by the number of reuse cycles to calculate the impacts per reuse cycle. It must be emphasized that the final end-of-life treatment of the insulation material was not described in this scenario. Each end-of-life scenario may still apply to the insulation material after the final use scenario, such as landfilling, incineration, or recycling into stabilizing agents for asphalt.

3.1.1.2 Allocation of impacts to the subsequent loop of cellulose insulation

Incineration/production of SRF: The impacts of energy valorization and the benefits of the substituted energy sources are already modeled in the first life cycle, in which energy was recovered at the EoL. The CFF does not include a term for *the use of* recovered energy, which would be relevant if parameter B were non-zero. Therefore, it is unclear from the CFF how to model the consumption of recovered energy. The most consistent approach, in line with the first life cycle, would be to model the consumption of heat and electricity from the same sources that were modeled as substitutes in the first life cycle. However, the PEF Guide's energy-use modeling allows for modeling in accordance with contractual agreements. If there were a contractual agreement with a provider of recovered energy, the recovery process and the potential benefits of using recovered energy would be double-counted across the first and the second life cycle. Therefore, it is recommended to apply the same energy production technologies in the first life cycle (as substituted) as in the second life cycle (as energy source).

Recycling into stabilizing agents in asphalt: The material-specific value $A = 0.5$ for cellulose insulation is applied to stabilizing agents derived from recycled cellulose insulation. This means that, even though the recycled content may be 100% (i.e., no primary stabilizing agents are used), the consumed material is 50% modeled by the recycling process of EoL insulation material, and 50% by the use of a stabilizing agent from primary sources. Also, there is no explicit guidance on how the specific primary additive that is substituted and reflected by the term "Ev" (see SI) must be determined. The quantity of primary additives needed is based on "how well" the additives displace one another, as represented by the quality correction factor.

Recycling into biochar for use as fertilizer: The use of biochar as fertilizer may be assimilated to "composting". According to the PEF Guide, for composting, a value of A = 0.5 shall be applied. This means that the use of biochar for fertilization is modeled at only 50% when produced from EoL cellulose insulation. The remaining 50% of this biochar input is modeled as Borax production. The quantity of Borax that is modeled shall reflect "how well" biochar may replace Borax, e.g., based on the boron content, which is captured by the quality correction term. It must be noted that the use of Borax for this application results in its leaching into the environment. However, as Borax is not actually used (but only biochar), only the leaching of particles associated with biochar is modeled in the use phase (e.g., hydrocarbons in groundwater). Therefore, there is a mismatch between the modeling of consumed

TABLE 2 Limitations of the PEF guide.

Limitation category	PEF guide
Errors and inconsistencies	• Collection rate and recycling efficiency rate are merged into one parameter, leading to erroneous calculations of recycling losses (Schrijvers et al., 2021a) • No parameter is included for *using* recovered energy, resulting in potential modeling inconsistencies between supplying and using recovered energy • Mandatory modeling of primary raw material use due to restricted options for parameter A, even if this is not corresponding with reality • Only substitution of primary materials is modeled, downstream effects of this substitution (e.g., differences in transport, use, or EoL) are not considere
Guidance needs	• Identification of the (substituted) primary raw material source • Identification of the (substituted) energy production source
Practical difficulties	• Final disposal of waste after multiple reuse cycles needs to be modeled, although the relevant processes may be unknown
Incentives	• A material that can be recycled multiple times in a cascading system will be assessed the same as a material that is only recycled once • Only materials that are recycled in a closed loop will benefit from multiple reuse cycles

raw materials and associated impacts downstream in the life cycle, since the CFF does not include a term for the downstream effects of using a recycled material instead of a primary material.

Reuse as insulation: Reuse for the same functionality extends the product's lifetime. Therefore, all reuse cycles are still considered part of the insulation's "first life cycle." The EoL insulation material enters a second life cycle only when it is recycled into a different application or valorized energetically after the final reuse cycle. In the second life cycle, the user of the valorized material/energy models the consumed valorized flows as described in the above scenarios.

3.1.2 EN 15804

The EN 15804 standard (AFNOR, 2022) formulates Product Category Rules (PCR) for the construction sector. These rules apply when developing Environmental Product Declarations in this sector. Due to the construction sector's lead in LCA application (driven by regulations), this PCR document has inspired LCA practice in other sectors as well. A detailed description of the modeling of multifunctional systems in accordance with EN 15804 is provided in the SI. The limitations of EN 15804 are summarized in Table 3.

3.1.2.1 Allocation of impacts to the preceding loop of cellulose insulation

All scenarios: The recycled content of end-of-life newspapers is modeled in Module A by recycling processes, starting from the "end-of-waste state" of the secondary material input flow. Only if virgin raw materials are used as well, virgin production is modeled in Module A. Waste treatment and/or recycling processes at the EoL are modeled up to the end-of-waste state of a produced valorized raw material or energy flow, if any.

Incineration with energy recovery: The end-of-life cellulose only reaches the end-of-waste state at the point of heat and electricity production. Hence, the incineration process is entirely modeled within Module C of the first life cycle. Benefits of the substitution of alternative energy production processes are modeled in Module D. The avoided energy source may be modeled as the energy source that is actually substituted. If this is unknown, the country-specific energy mix is used for the country where the substitution occurs (AFNOR, 2022).

Production of SRF: In the case of the production of Solid Recovered Fuels, the end-of-waste state may already be determined at the moment when the fuel is produced. Subsequent processes, such as transport and combustion, are modeled in Module D, along with the benefits of substituting alternative energy production processes. Similar to the case of incineration, the avoided energy source may be modeled as the energy source that is actually substituted. If this is unknown, the country-specific energy mix is used for the country in which the substitution takes place (AFNOR, 2022).

Recycling into stabilizing agents in asphalt: Recycling of the EoL cellulose is modeled up to the end-of-waste state in Module C, which is here determined as the production of the stabilizing agent. No additional processing is required for Module D; it only addresses the benefits of substituting an alternative stabilizing agent in asphalt. A value-correction factor is applied to calculate the actual quantity of virgin material displaced. The specific primary additive that is substituted is based on the current average technology or practice (CEN, 2012).

Recycling into biochar for use as fertilizer: The end-of-waste stage in this scenario is determined at the point of biochar production. Therefore, pelletization and pyrolysis are included in Module C. However, it might be justifiable to determine the end-of-waste state after the pelletization process. In the latter case, pyrolysis would be included in Module D. Under the current definition of the system boundaries, Module D includes only the benefits of substituting for Borax production. Any additional downstream consequences of substituting Borax with biochar, such as differences in leaching, are outside the scope of the assessment.

Reuse as insulation: The EoL of the insulation material is defined at the moment that the material is removed from its application. Any manipulation of the material until it becomes ready for reuse (i.e., up to the end-of-waste state) is part of Module C. The benefits of displacing a primary material by reusing the insulation are modeled in Module D.

TABLE 3 Limitations of EN 15804.

Limitation category	EN 15804
Errors and inconsistencies	• Only substitution of primary materials is modeled, downstream effects of this substitution (e.g., differences in transport, use, or EoL) are not considered
Guidance needs	n.d.
Practical difficulties	• Determination of "end-of-waste state" may be difficult, where multiple interpretations and/or practices could lead to variation in the modeling
Incentives	• A material that can be recycled multiple times in a cascading system will be assessed the same as a material that is only recycled once • Technically, if only recycled materials are used as input, and no recycling takes place at the EoL, the net outflow of recycled materials is negative. Some users of EN 15804 may consider that Module D must model the effects of this negative output of recycled material, such as an increased production of primary materials. However, as Module D is optional, this is rarely applied in practice. In most cases, when the recycled content is higher than the end-of-life recycling rate, the net output of recycled materials is put at zero. This perspective has been adopted in the description of the method in this report. Therefore, recycling may only be reported if it leads to additional benefits in a life cycle, and not if it leads to additional impacts

3.1.2.2 Allocation of impacts to the subsequent loop of cellulose insulation

Incineration with energy recovery: The impacts of incineration are already modeled in the first life cycle. The user of the recovered energy can use it burden-free.

Production of SRF: The user of the SRF models the transport and combustion process, which are the processes downstream of the "end-of-waste state" of the SRF.

Recycling into stabilizing agents in asphalt: As the end-of-waste state of the stabilizing agent is determined at the point of production, no further recycling processes are modeled by the user; the product is burden-free.

Recycling into biochar for use as fertilizer: Similar to the stabilizing agent, the biochar is used burden-free, as the production of biochar is determined to be the end-of-waste state of the end-of-life insulation material.

Reuse as insulation: In this example, the second user of the cellulose insulation material does not model any recycling/reuse steps, as the previous user modeled these. However, if at the EoL the insulation material is prepared for a second reuse cycle (for a third user), preparatory processes are modeled in Module C of the second user. Benefits of reuse, by the substitution of a primary insulation material, are only modeled for the *net* output of reused insulation material, i.e., the quantity of reused insulation material made available at the EoL *minus* the quantity of reused insulation material as an input material. This net value can only be positive if the second life cycle also includes a fraction of virgin material input. If the net output value is negative, either negative benefits (i.e., additional impacts) may be modeled in Module D, or the benefits of Module D may be considered as zero. The latter option, of course, results in a lower environmental impact attributed to the second life cycle.

3.1.3 Allocation at the point of substitution

Allocation at the point of substitution (APOS) applies to co-products, recycled materials, and recovered energy. The method had been introduced by Weidema (2018), and was applied as a separate system model in ecoinvent v.3 (Wernet et al., 2016). Schrijvers et al. (2021a) clarified the underlying assumptions (i.e., "axioms") and definitions on which the APOS method is based, which provide a scientific justification for the application of the method. A more detailed description of the APOS method is provided in the SI. The limitations of APOS are summarized in Table 4.

3.1.3.1 Allocation of impacts to the preceding loop of cellulose insulation

All scenarios: To model the recycled content, it must be determined which environmental impacts are attributable to cellulose from EoL newspapers. Following Axiom 1 (see SI), the processes that are required to make cellulose from EoL newspapers are newspaper production and newspaper recycling. These processes constitute the "production system" of cellulose from EoL newspapers. However, these processes are also part of the product system of newspapers. Newspapers and cellulose from EoL newspapers are therefore considered as co-products from the same production system. Following Axiom 2 (see SI), the environmental impacts of this production system are partitioned between the newspapers and the cellulose insulation based on the relative economic revenue that they generate for the system.

Incineration with energy recovery: System boundaries are drawn to show the processes that are required to produce recovered energy. Recovered heat and electricity are co-products of cellulose insulation. Partitioning is applied to these flows based on the relative economic revenue they generate. Therefore, cellulose insulation *and* recovered heat and electricity are partly accountable for the production of newspapers, newspaper recycling, the manufacturing of cellulose insulation, and the incineration process.

Production of SRF: System boundaries are drawn to show the processes that are required to produce the SRF. As the output of a production process can only be a product or an elementary flow, the system boundaries are put when the output flow may be considered "a product". According to the definition applied here, this point coincides with the "end-of-waste state" of EN 15804, i.e., the moment that SRF are produced. SRF is then a co-product of cellulose insulation. Partitioning is applied

TABLE 4 Limitations of allocation at the point of substitution.

Limitation category	APOS
Errors and inconsistencies	n.d.
Guidance needs	• Although APOS provides a purely attributional LCA perspective, no industrial standard has adopted APOS as the recommended allocation methodology. Therefore, it has mostly been used in the scientific domain • The APOS method is relatively new, which makes that the axioms and definitions provided by Schrijvers et al. (2021a) have not yet followed an international consensus-building and validation procedure • The definition of "end of life" is still open for interpretation. For example, in the case of reuse, the EoL may be after a first use, or after all potential uses. A definition needs to be agreed upon within the LCA community that allows for a consistent application of APOS across uses in this situation
Practical difficulties	• Recycled materials carry part of the impacts of their previous life cycle(s), which may be cumbersome to model if no data are available from background databases • Determination of "end-of-waste state" (i.e., when a waste becomes a "co-product") may be difficult, where multiple interpretations and/or practices could lead to variation in the modeling
Incentives	• Future recycling or cascading loops are beyond the scope of the assessment, only recycling into one subsequent life cycle is considered. Therefore, a material that can be recycled multiple times in a cascading system will be assessed the same as a material that is only recycled once

to these flows based on the relative economic revenue they generate. Consequently, cellulose insulation *and* SRF are partly responsible for the production of newspapers, newspaper recycling, the manufacturing of cellulose insulation, and the sorting, grinding, and pelletizing processes. The user models the transport and combustion processes that occur downstream of the SRF's "end-of-waste state."

Recycling into stabilizing agents in asphalt: System boundaries are drawn (in the SI) to show the processes that are required to produce the stabilizing agents. As the output of a production process can only be a product or an elementary flow, the system boundaries are put when the output flow may be considered "a product". Here, this is considered at the produced flow of "stabilizing agents". Stabilizing agents are then a co-product of cellulose insulation. Partitioning is applied to these flows based on the relative economic revenue they generate. Therefore, cellulose insulation *and* stabilizing agents are partly accountable for the production of newspapers, newspaper recycling, the manufacturing of cellulose insulation, and the entire recycling process.

Recycling into biochar for use as fertilizer: Similar to the stabilizing agent, the biochar is a co-product of cellulose insulation. Both flows are accountable for the impacts of newspaper production, newspaper recycling, insulation manufacturing, and the pelletization and pyrolysis of EoL insulation materials.

Reuse as insulation: In this scenario, the key question is how the EoL of cellulose insulation is defined—either after a first use, similar to EN 15804, or after all potential uses (e.g., three or four uses), such as in the PEF Guide. The definition of "end of life" in the SI allows for both interpretations, as "intended use" may be specific to a building or to the material itself. In Supplementary Figure 8, the same interpretation as in EN 15804 is applied. Following this, the first and second uses of the cellulose insulation are both co-products of the production system, which includes processes for cellulose manufacturing and preparation for reuse. In this interpretation, the first user of the insulation does not model its final disposal (e.g., after three uses). This may be justified, as the final disposal is beyond the control of this first user and may take place over an extended timeframe (e.g., 100 years, given the long lifetimes of buildings). Furthermore, this interpretation allows consideration of quality loss across different reuse cycles, as the first and second uses may not yield the same economic revenue (a material that has been used three times before may be cheaper than a new material).

3.1.3.2 Allocation of impacts to the subsequent loop of cellulose insulation

Incineration with energy recovery: The user of recovered energy is accountable for impacts associated with the production and incineration of cellulose insulation. If the relative economic value of recovered energy is low compared to the revenue generated by cellulose insulation, the impacts of recovered heat and energy may become negligible and approach "burden-free".

Production of SRF: The user of the SRF is partly accountable (defined by the relative economic revenue) for the impacts of the production of the cellulose insulation and the formulation of the SRF. The user is furthermore entirely accountable for the transport and combustion of SRF.

Recycling into stabilizing agents in asphalt: The user of the stabilizing agent is partly accountable (defined by the relative economic revenue) for the impacts of the production of the cellulose insulation and the recycling of insulation into the stabilizing agent. Further downstream processes related to asphalt manufacturing are entirely modeled by the user.

Recycling into biochar for use as fertilizer: The user of the biochar is partly accountable (defined by the relative economic revenue) for the impacts of the production of the cellulose insulation and the pelletization and pyrolysis for the transformation of insulation material into biochar. Further downstream processes related to biochar use are modeled by the user.

Reuse as insulation: The second user of the cellulose insulation material is partly accountable (defined by the relative economic value compared with the first user) for the impacts of producing the cellulose insulation and preparing it for reuse. At the EoL of the second use, the material is prepared for a third reuse cycle. The cradle-to-gate impacts of the second use of the material, plus the preparatory processes for the third use, are partitioned between the second and third users based on the relative economic revenue they generate. If it is unknown how often the material has been used before, or if the used insulation material contains a mix of virgin, first, second, and third cycle material, a formula is provided by Schrijvers et al. (2016a) to calculate the average impacts attributable to a single use cycle of the material.

3.1.4 Consequential LCA

Consequential LCA is an LCA approach that assesses the effects of a change, also referred to as the effects of a decision, often expressed as an increase or decrease in demand for a particular product or service. Unlike in an attributional LCA, where the impacts of processes are assessed that appear in a product's supply chain, a consequential LCA only assesses the impacts of processes that are *affected* by the studied change. A detailed description of the consequential LCA approach applied in this paper is presented in the SI. The limitations of this consequential LCA approach are summarized in Table 5.

3.1.4.1 Allocation of impacts to the preceding loop of cellulose insulation

All scenarios: As the recycled flow of cellulose from EoL newspapers is known to come from a recycling process, the recycling process is put within the foreground system. The flow of "EoL newspapers" comes from the background subsystem, meaning it is taken from the generic market. This flow is modeled as "increased demand dependent intermediate flow" (see SI). Via parameter "A", it is determined whether the demand for EoL newspapers is constrained ($A = 0$) or unconstrained ($A = 1$). If EoL newspapers are currently (partly) disposed of as waste, it may be considered that supply is higher than demand, and demand is constrained ($A = 0$). A value of $0 < A < 1$ may be regarded as an average over different geological locations (Schrijvers et al., 2021b). For illustrative purposes, the value of $A = 0.3$ is applied here. This means that using EoL newspapers as an input in the cellulose recycling process results in 70% substitution for the marginal waste treatment of these EoL newspapers, such as replacing incineration with energy recovery. To the extent that demand is unconstrained (there is sufficient demand for EoL newspapers in the generic market), i.e., 30%, it is considered that taking this flow from the market avoids the flow being recycled by the marginal valorization process of EoL newspapers. This recycling process could, for example, be the closed-loop recycling of newspapers. The marginal user of recycled newspapers must now find another raw material source, such as primary pulp, to produce newspapers. Any additional differences between using recycled newspapers or primary pulp, such as during transport or end-of-life treatment, noticed by this marginal user, are modeled as indirect downstream effects. As a result of using recycled material that is already high in demand, using EoL newspapers as recycled content in cellulose insulation is only environmentally beneficial if the benefits of displacing alternative raw materials in the insulation industry are higher than the benefits of displacing alternative raw materials in the newspaper industry. Benefits can furthermore be obtained by proposing a recycling process that is more efficient or less impactful than the marginal recycling process.

Incineration with energy recovery: In the SI, system boundaries are shown in accordance with the market-driven substitution formula, which is a simplified interpretation of the cause-and-effect relationships described in the SI. The energy valorization process is drawn within the foreground subsystem. The incineration process produces heat and electricity, based on the conversion efficiency of the process (parameter "C" in the SI). It was assumed in the construction of the formula that the demand for recovered energy is unconstrained (A =1). Therefore, the recovered energy is assumed to be used by the marginal user, and the production of energy via the marginal production process is substituted. It is assumed that there no further differences for the marginal user between using recovered energy and another energy source. In some cases, the assumption that there is sufficient demand for recovered energy might not hold. For example, in certain months of the year or in certain circumstances, there may be a surplus of produced heat. In that case, instead of following the substitution formula, the effects must be modeled via the diagram of the SI. A constrained demand for heat could mean that heat from another source ceases to be valorized, or that more heat is wasted through the internal systems of the marginal users of the heat. In that case, substitution of the production of heat via the marginal production process is not justified.

Production of SRF: Instead of following the term for energy recovery in the market-driven substitution formula, the effects as depicted in the causal loop diagram in the SI are followed, which provides a more detailed reflection, although the modeling principles are the same. In this scenario, the boundaries of the foreground subsystem are put at the production of the SRF material, which is sold on the market. A benefit of producing SRF, compared to incineration with energy recovery, is that the recovered energy is available at the time and location where it is needed. Therefore, the assumption that the demand for SRF is unconstrained ($A = 1$, there is always sufficient demand) is justified. Supplying SRF to the market results in an increased use by the marginal user (the user that is most likely to increase its consumption of SRF), which subsequently decreases its demand for an alternative energy source. If the SRF is directed to a specific market, such as the cement industry, the substituted marginal energy production is identified for that market, which may be, for example, coal-based rather than natural gas-based (or a mix with renewable energy sources) in the generic energy market. Indirect downstream effects observed by the marginal user include differences in the transport of SRF and in emissions from SRF compared to the alternative energy source (e.g., coal).

Recycling into stabilizing agents in asphalt: Valorization of the EoL insulation material is modeled as part of the foreground system, up to the point at which stabilizing agents are sold to the market. Parameter A indicates whether all the EoL insulation material may be transformed into stabilizing agents, or whether demand for this application is limited. For illustrative purposes, a value of $A = 0.5$ is taken, indicating that demand may be well developed in some areas. In contrast, in other places, there may be a surplus of these types of stabilizing agents.

TABLE 5 Limitations of consequential LCA.

Limitation category	Consequential LCA
Errors and inconsistencies	n.d.
Guidance needs	n.d.
Practical difficulties	• Data are needed for both foreground processes (processes under control by value-chain actors) and background processes (marginal production, waste treatment, and valorization processes), whereas the existence of background databases is underdeveloped. The use of the consequential system model of ecoinvent v3 provides a good starting point for most important flows, although recycling processes may be underrepresented in this database, as well as marginal production and waste treatment processes specifically for biobased materials. Data may be used from other sources, but, as most other sources provide attributional data, remodeling must be done to make the data compatible with the consequential model (e.g., modeling of substitution of co-products instead of partitioning). Furthermore, if data are missing from the database, an effort is required to identify the marginal process among a mix of currently available processes • Strong dependence on market data, either provided by market research or approached by assumptions, to determine demand constraints (i.e., the parameter value for A) and potential substitutes.
Incentives	n.d.

As a consequence, 50% of the supplied stabilizing agents may substitute for the production of alternative stabilizers. Here, the marginal stabilizer must be identified (the stabilizer for which it is most likely that the production volume will be decreased). Furthermore, any differences in the asphalt life cycle must be taken into account, including potential leaching of the stabilizer, maintenance requirements, and differences in treatment at the EoL. The remaining 50% of the supplied stabilizer may result in a decrease in waste valorization for this purpose in other product systems, such as other sources of insulation material or other types of (organic) materials. These wastes are now increasingly treated through marginal waste treatment processes, such as incineration. The affected processes may be identified by market research or by making simplifying assumptions, such as that the affected valorization processes in the market are similar to the valorization process in the foreground system.

Recycling into biochar for use as fertilizer: The production of biochar is modeled within the foreground system. The effects of introducing biochar to the market are dependent on parameter A. Also here, for illustrative purposes, a value of $A = 0.5$ is taken. This means that the supply of biochar is modeled at 50% as the substitution of Borax. The downstream effects of this substitution (decreased leaching of Borax, increased leaching of hydrocarbons) are modeled as well. For the remaining 50%, the biochar market, including similar materials, is already saturated. The increased supply of biochar results in a decrease in the valorization of organic materials in other product systems and a subsequent increase in alternative waste treatment (e.g., incineration).

Reuse as insulation: In the case of reuse, the choice of where to set the system boundaries depends on the level of control over the reuse chain held by the involved stakeholders. If reuse is guaranteed by the manufacturer, for example, by the implementation of a product-service system, the reuse cycles remain within the foreground subsystem, and only the final disposal process is modeled by the marginal disposal process in the background system. The system boundaries of the foreground system may then coincide with the system boundaries in the application of the CFF (Supplementary Figure 4). However, if reuse is left to market dynamics, the question is whether demand for reused insulation is saturated (as depicted in Supplementary Figure 12). Reusable insulation material may compete with other types of reusable insulation material or with insulation material from (different types of) recycled materials. Also, here, the determination of the marginal valorization process for insulation material may be based on market research or simplifying assumptions.

3.1.4.2 Allocation of impacts to the subsequent loop of cellulose insulation

Incineration with energy recovery: If the user of the recovered energy were to purchase the energy on the market, the flows "heat" and "electricity" would enter the foreground system. Following the assumption mentioned above that the demand for recovered energy is unconstrained, using recovered energy results in a decrease in its use by the marginal user, who will increase their consumption of energy from alternative sources, as modeled via the marginal production processes. However, if the user of recovered energy is responsible for the recovery process, it purchases cellulose insulation rather than recovered energy on the market. This is illustrated in Supplementary Figure 13. Here, it must be assessed whether the demand for EoL insulation material is constrained. Again, a value of $A = 0.5$ is used for illustrative purposes. With this value, 50% of the flow of EoL insulation material is assumed to be diverted from its marginal waste treatment process (i.e., substituted waste treatment). This may be local landfilling or incineration with energy recovery. Note that, if incineration with energy recovery is substituted, an additional energy production process must be modeled to supply the energy that would otherwise be produced, assuming that the demand for energy in other life cycles remains stable. The remaining 50% of the consumed flow of EoL insulation material is assumed to be otherwise valorized by the marginal valorization process. One could imagine exports to other countries for low-value valorization, substituting raw material needs in remote economies. Such information may be provided by market research or LCA databases.

Production of SRF: The system boundaries (in the SI) show that the SRF is purchased on the market. Therefore, the valorization of insulation material into SRF is not part of the foreground system. Considering that demand for SRF is unconstrained, the additional use of SRF results in a decrease in SRF use by its marginal user and an increased production of an alternative product (i.e., energy source) by the marginal production process. Mirroring the effects of supplying SRF to the cement industry market, this marginal production process may be the production of energy from coal. In addition, the user of SRF under study models the emissions associated with coal use and subtracts the emissions related to SRF use, as observed by this marginal user. In practice, it could mean that the combustion of SRF in the foreground system is offset by reduced combustion in the background system and replaced by emissions associated with coal use in the background system.

Recycling into stabilizing agents in asphalt: As with SRF, the stabilizing agent from cellulose insulation is bought on the market. The same value for demand constraints (A) is taken as for the supplier of the valorized material: $A = 0.5$. This means that the life cycle of the asphalt models for 50% the additional valorization and the avoided waste treatment of a similar EoL material as the cellulose insulation, mirroring the effect of the additional supply of stabilizing agent from cellulose insulation. The remaining 50% of this recycled input flow is modeled as a decrease in its use by the marginal user, with a subsequent increase in production of an alternative product, as well as downstream effects in the background system of using the alternative product instead of the stabilizing agent from cellulose insulation.

Recycling into biochar for use as fertilizer: Here, too, modeling follows the same pattern as for the use of stabilizing agents in asphalt, depending on the parameter A. If $A = 0.5$, as assumed in the case of the supplying life cycle, the use of biochar is modeled for 50% as an increased valorization of similar EoL materials and substituted marginal waste treatment of these materials. For the remaining 50%, the use of biochar results in decreased use by the marginal user (assumed also to be the fertilizer application), with Borax now used instead. This results in an increase in Borax production, along with downstream effects related to its use (e.g., leaching), minus the effects of biochar use in the background system. This means that the leaching of hydrocarbons in groundwater, as modeled in the foreground system, may be offset by the avoided leaching in the background system, and compensated by an increased leaching of Borax in the background system.

Reuse as insulation: System boundaries (in the SI) are aligned with the supplying life-cycle system boundaries; i.e., it is assumed that the reusable insulation material is traded on the market. Depending on the value of A, the demand for reusable insulation material is partly modeled by the additional valorization of similar EoL material and substituted waste treatment, and partly by a decrease in the use of reusable insulation material by the marginal user and an increase in the production of an alternative material. If the insulation material is made available for reuse in another round, the mirrored effects are modeled at EoL. This means that, as long as the recycled content equals the end-of-life recycling rate, it does not matter for environmental impacts whether reuse is organized through the market or within the boundaries of a single company. However, the market situation (demand constraints) influences the types of effects modeled by these exchanges with the market. If demand is low, the focus is on increased/decreased valorization in the market and decreased/increased waste treatment, respectively. However, if demand for the material is generally high, the focus is on the decreased/increased use by the marginal user and increased/decreased production of an alternative material. If demand is low, it is often more favorable to focus on *using* recycled material, while if demand is high, the additional *supply* of recycled materials results in lower impacts (as long as recycling generates lower impacts than primary production, that is).

3.1.5 Process-oriented LCA from the recycler/valorizer perspective

Whether a waste should be valorized to generate environmental benefits (e.g., compared to its non-valorization) does not necessarily require a product perspective, as applied in the sections that focus on the first and second life cycles associated with the valorization process. Instead, a process-oriented perspective could be applied [as introduced by Schrijvers et al. (2020a)], which focuses on the processes that are affected by the implementation of a valorization process. The limitations of a process-oriented LCA from the recycler/valorizer perspective are noted in Table 6.

The system boundaries of an LCA study from the perspective of the recycler, for the different EoL scenarios of cellulose insulation, are shown in Supplementary Figure 14. In line with the functional unit (see Supplementary Table 1), the system boundaries show a flow of incoming waste and an outgoing product (energy or material). The inputs are not "burden-free"; they are the *subject* of the analysis. In a comparative LCA, where, e.g., two scenarios are compared with one another, the sizes of the incoming and outgoing functional flows must be equivalent.

If a scenario does not produce the same functional output as a compared scenario, additional processes can be added to the system boundaries. For example, the landfilling scenario does not provide a functional output from the end-of-life treatment processes. If landfilling were compared to incineration with energy recovery, for example, an additional energy production process may be added to the landfilling scenario, as illustrated in Supplementary Figure 14A.

If there are upstream or downstream differences between the two scenarios beyond the boundaries of the recycling or valorization processes, ideally, the system boundaries are extended to include the life-cycle stages where these differences occur. For example, in the case of biochar production, if this scenario is compared to one in which Borax would be used as a fertilizer, ideally, the use phase would be included within the system boundaries to account for the different emissions from leachate.

By applying system expansion, there is no need to allocate the impacts or benefits of circular processes across different life cycles.

3.1.6 Multi-life cycle approach

Most of the above methods for assessing environmental impacts related to a circularity strategy focus on a product (e.g., a recycled product). Such a focus requires the application of an allocation procedure (here, substitution is also called an "allocation procedure"). According to ISO 14044, ideally, allocation is avoided through system expansion. System expansion may be applied at the process level, where multiple functional flows of a process are included within the functional unit. This level was applied to the "recycler perspective" in the previous section. However, an expanded system may also comprise multiple life cycles or loops

TABLE 6 Limitations of the recycler/valorizer perspective.

Limitation category	Recycler/valorizer perspective
Errors and inconsistencies	n.d.
Guidance needs	n.d.
Practical difficulties	n.d.
Incentives	• The scope is limited to the processes that are included in the recycling/valorization chain. This means that only the environmental benefits of these processes are assessed. No information is provided about a specific product life cycle, and circularity strategies that aim to decrease the impact of a product are not represented by this approach. For example, the benefits of increasing the end-of-life recycling rate are out of scope of the analysis, as only the share that is recycled will be assessed by this approach

(i.e., the entire chain) that are affected by the implementation of a circularity strategy. This is the ideal approach to identify the environmental benefits of circularity, as it provides a complete overview of all effects of the circularity strategy across each subsequent life cycle and requires no allocation decisions. The limitations of the multi-life cycle approach are mentioned in Table 7.

The system boundaries (Supplementary Figure 15) cover all loops of the circular scenario. Note that if a linear system does not cover the same product functionalities over multiple life cycles as a circular system, the linear system should model multiple independent product systems within its system boundaries to make the two systems comparable. This is illustrated in Supplementary Figure 15A for the landfilling scenario.

Similarly to the recycler perspective, no allocation of impacts is done between the consecutive loops.

3.2 LCA method selection for modeling of circularity strategies based on goal and scope

From the previous section, it became clear that multiple LCA approaches can be used to model the circularity aspects of a product and its life cycle. Each LCA approach models a product's circularity differently, potentially leading to significant differences in the impacts assessed by the methods. Key factors that justify selecting one approach over another include aspects of the LCA's Goal and Scope definition.

The first observable difference between the LCA Goal and Scope of the evaluated LCA methods is the scope of the system, i.e., the processes included within the system boundaries. Three scopes of assessed systems are observed. The PEF method, EN 15804, APOS, and the consequential LCA approach all model a product from cradle (resource extraction by unconstrained suppliers) to grave (here, end-of-life treatment). The process-oriented LCA from the recycler/valorizer perspective applies a gate-to-gate approach, focusing on a selection of processes from a product's life cycle within its system boundaries. The multi-life-cycle approach applies a cradle-to-grave approach, in which product loops are added to the system boundaries if end-of-life treatment processes valorize waste flows. These different system scopes are associated with other functional units, as specified in Supplementary Table 1.

A second difference in the LCA Goal and Scope of the assessed LCA methods is the impact scope. In the methods section, the difference between attributional and consequential LCA was introduced. Whereas, the "consequential LCA" method is obviously consequential, the impact scope of other methods is less explicit. In practice, standardized LCA approaches rarely apply a purely attributional or consequential perspective (Schrijvers et al., 2016b). Therefore, we interpret "attributional" LCA as "normative" LCA, which applies normative rules to determine which impacts are attributable to which products. Normative LCA approaches aim to assess a product's environmental footprint, based on agreed-upon rules among a selection of stakeholders, which can be representatives from governmental institutions [e.g., the Product Environmental Footprint (PEF) Guide (European Commission, 2021)], industry associations [e.g., EN 15804 for the construction sector (CEN, 2012)], and/or the scientific community [e.g., Allocation at the Point of Substitution (APOS) (Schrijvers et al., 2021a)]. These rules reflect a consensus among the involved parties on "for which environmental impacts a product is accountable", which is unavoidably subjective (Schrijvers et al., 2021a). These rules are documented in a standard or guideline that further defines methodological choices beyond the ISO 14040-14044 framework. Such LCA approaches may be based on a mix of attributional and consequential elements, as is the case for the PEF guide and EN 15804 (considering Module D) (Schrijvers et al., 2016b). Only the APOS method may be considered purely attributional, given its consistent application of partitioning. If the Goal and Scope of an LCA study describe the impact scope as attributional, the choice between the PEF Guide, EN 15804, or APOS can be made based on the LCA results' reporting context, as this determines which attribution choices are accepted by the study's target audience. The process-oriented LCA from a recycler/valorizer perspective and the multi-life-cycle approach apply to both attributional and consequential LCA. Note that, as the functional flows of a process-oriented LCA are not characterized themselves, no market assessment is required for those in a consequential LCA.

Examples of research questions for all LCA methods, including distinctions between attributional and consequential impact scopes, are provided in Supplementary Table 1. The selected impact scope furthermore extends to the selection of the background database for modeling intermediate flows, which can be attributional or consequential.

The selection of LCA methods based on the definition of specific attributes of the LCA Goal and Scope, as described above, is mapped for the system scope "product" in Figure 2, for the scope

TABLE 7 Limitations of the multi-life cycle approach.

Limitation category	Multi-life cycle approach
Errors and inconsistencies	n.d.
Guidance needs	n.d.
Practical difficulties	n.d.
Incentives	• The scope is extended to comprise multiple life cycles, which gives a complete vision of all life cycles affected by a recycling chain. However, a limitation is that no information is provided at a product level. As no allocation procedure of impacts among the different life cycles is applied, claims about the specific footprint of a single life cycle are not supported

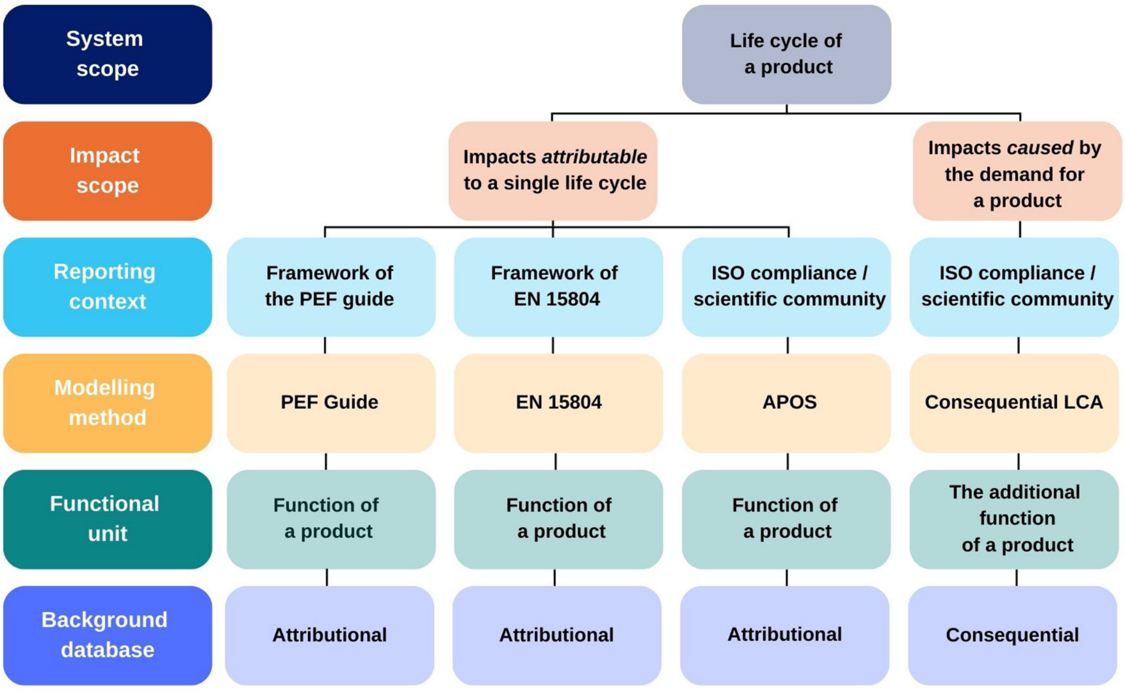

FIGURE 2
LCA method selection for studies focusing on the life cycle of a product.

of (a) specific process(es) in Figure 3, and for multiple subsequent life cycles in Figure 4.

3.3 LCA method coverage of circularity strategies and complementary use of circularity indicators

A comprehensive list of circularity strategies was developed that could make products and/or processes more sustainable. Not all LCA methods can demonstrate the benefits of all circularity strategies. An overview of which circularity strategies are covered by which method is provided in Supplementary Table 5. A more detailed version of the table, with a justification for the classification of the circularity strategies (e.g., inclusion vs. exclusion), is provided in a Supplementary Excel file. A graphical representation of Supplementary Table 5 is provided in the SI, showing the coverage of circularity parameters across different LCA and circularity methods. An interactive version of this network is available at https://public.flourish.studio/visualisation/20148285/.

The most comprehensive LCA method is Consequential LCA, which can be used to show the potential benefits of 42 circularity strategies. The PEF guide is the second-most comprehensive LCA methodology, whereas the system-expansion approach from the perspective of the recycler is the most restrictive (covering only 13 circularity strategies). When looking at Circularity Indicators, these cover 22 (CTI) to 9 (ISO 59020) circularity strategies.

It may be the case that the selected LCA method, based on the goal and scope of an LCA study as presented in the previous section, does not reflect a specific circularity strategy, which is, however, implemented by the stakeholder interested in the study's results. Then, a complementary assessment may be conducted to represent the additional benefits generated by this specific circularity strategy. From Supplementary Table 5, complementary LCA methods or Circularity Indicators can be derived for each LCA modeling method and for each circularity strategy. For example, if the PEF Guide is used to assess the environmental impacts of a recyclable

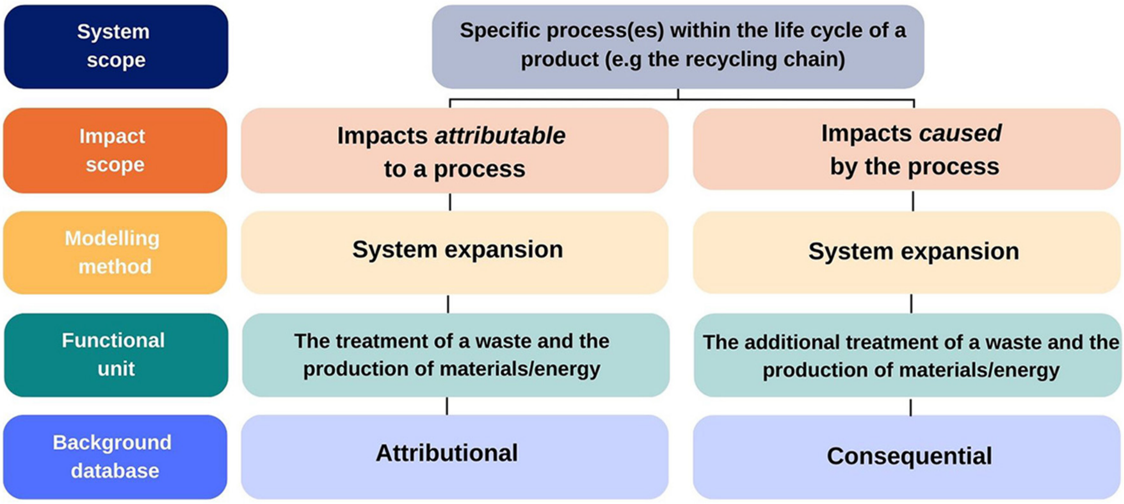

FIGURE 3
LCA method selection for studies focusing on selected processes within a life cycle.

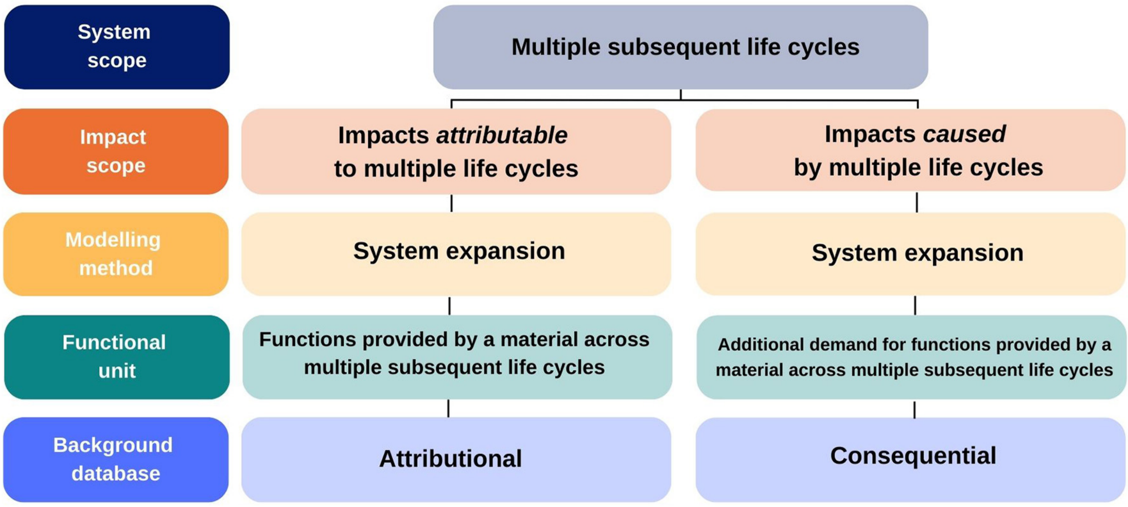

FIGURE 4
LCA method selection for studies taking multiple life cycles into account.

product at EoL, the potential benefit of enabling the use of a material across multiple loops in cascades is not well represented by the PEF Guide. As complementary information, the CTI method may be used to show the benefits of increased efforts made in this area. This tandem approach to applying an LCA method and (a) Circularity Indicator(s) is summarized in Figure 5.

4 Discussion

This paper demonstrates the application of 6 LCA approaches (the PEF Guide, EN 15804, Allocation at the Point of Substitution, consequential LCA, and two process-oriented LCA types) to model circularity strategies, including recycling, reuse, and cascading use of bio-based materials.

The limitations of the assessed LCA approaches are presented in Tables 2–7. These limitations include errors and inconsistencies identified in the PEF Guide and EN 15804. Both guidelines consider only the substitution of primary materials, disregarding their downstream effects. This results in strange outcomes for users of recycled material following the PEF Guide, who need to model primary production without accounting for the consequences of using a primary material (e.g., borax leaching in the biochar scenario). This could be resolved by adding a term in the CFF and in Module D of EN 15804 for the downstream effects of substitution. Other errors in the CFF include a lack of distinctive parameters for the collection rate, recycling efficiency rate, and the use of recovered energy, which were already mentioned by Schrijvers et al. (2021b), and here illustrated by the case study. Together with a limited range of parameter A values, impacts calculated by the PEF method risk being inconsistent with actual product and emissions flows. The

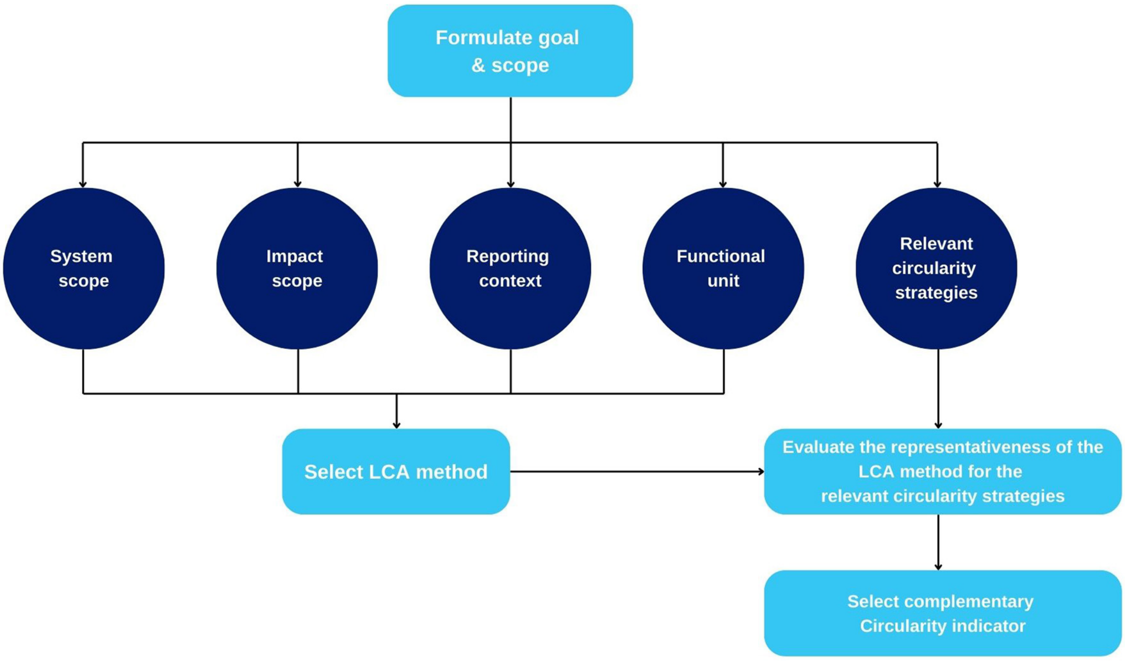

FIGURE 5
Framework for selecting complementary LCA methods and circularity indicators for the assessment of circular systems.

CFF could be adapted to explicitly include parameters for these aspects, as well as allowing for a value of *A* between 0 and 1.

Furthermore, for the PEF Guide and the APOS method, needs for further guidance are formulated, which may be considered in an update (of the PEF Guide) as well, or in the development of a new guidance document (for APOS) altogether. The application of the PEF Guide could be facilitated by additional guidance on the substituted primary raw material and energy production sources (e.g., the European average, a marginal technology, the worst- or best-performing technology, or a specific benchmark). For the APOS method, a guidance document validated by industry stakeholders is lacking, and an international consensus-building and validation procedure of definitions (such as of the term "end of life") and underlying axioms is required to make it a widely applicable and recognized allocation procedure.

For the PEF Guide, EN 15804, APOS, and consequential LCA, practical difficulties may arise in their application. This includes identifying the "end-of-waste state" in both EN 15804 and the APOS method. Also, assumptions are required of unknown processes, such as upstream life cycles in the APOS method, and downstream waste treatment after multiple reuse loops in the PEF method. A lack of compatible databases limits the selection of data for a consequential LCA. Furthermore, assumptions may be needed to determine demand constraints and potential substitutes. However, the A-values as communicated by the European Commission for the application of the CFF (European Commission, 2020) may provide a starting point for identifying demand constraints in a consequential LCA, as these values have been developed to represent the market situation for recycled/recovered materials. Overall, practical difficulties in all modeling approaches may be addressed by simplifications, uncertainty, and/or scenario analyses.

Finally, each method, apart from consequential LCA, is limited to the applicable system boundaries and the corresponding incentives they provide. For example, as the PEF Guide and APOS do not well represent (future) cascading systems, these approaches offer no incentive to make materials recyclable over multiple (future) loops. These limitations may be overcome by combining multiple assessment methods (as outlined in Supplementary Table 5) to provide a multi-angle view of the system's environmental sustainability.

Structured guidance is offered for selecting the most appropriate modeling method based on the goal and scope definition of the LCA study. The presented work furthermore clarifies which LCA modeling methods and Circularity Indicators can be used or combined to demonstrate the potential benefits of implementing circularity strategies, of which we analyzed 48. Our analysis highlights that the coverage of circularity strategies varies significantly across LCA methods. It can be observed that there is much overlap between the circularity strategies covered in most LCA methods. Only the following 5 circularity strategies were not at all covered by any LCA method:

- The "*fraction of a product from Sustained Production going to energy recovery*" is considered circular in the MCI under strict conditions, such as that the product must be from a biological source, and other EoL options (besides landfill) are not practically or economically feasible (Goddin et al., 2019). In LCA, energy recovery results in emissions that depend on the energy recovery process and the product composition, but not on the product origin. Variations in environmental impact associated with the product's origin are reflected in its consumption, not in its end-of-life treatment.

- "*Maximizing the recovery potential up to theoretical limits*", covered by ISO 59020 (ISO, 2024a) is not reflected in LCA, as only *actual* recovery rates are considered in the assessment, which are automatically below the theoretical limit. A scenario analysis may be of interest to determine whether increasing the recovery rate could lead to environmental benefits, as reflected in the strategy "increase the EoL recovery rate". The gap between the current recovery rate and the theoretical limit is not considered to provide relevant additional information about a product's environmental performance.
- "*Increasing the revenue generated relative to the total mass of linear resource inflows*" is a material productivity factor that can be optimized by either increasing the revenue generated by a product or decreasing the mass of linear resource inflows. This is an optional attribute considered in CTI and ISO 59020. It reflects the potential economic benefits of adopting a more circular product system, which falls under the economic pillar of sustainability and is therefore not included in an environmental LCA but rather in an overarching LCSA.
- "*Using less critical raw materials*" is suggested as an optional circularity strategy in the MCI and CTI methods. Although there have been efforts to develop impact methods to assess raw material criticality in the context of an LCA [e.g., GeoPolRisk and ESSENZ (Cimprich et al., 2019)], these methods generally determine criticality at the level of elementary flows, not at the level of a product's bill of materials. Furthermore, criticality assessment is usually recommended as a complement to environmental LCA within an LCSA framework, given its socio-economic aspects (Sonnemann et al., 2015; Hackenhaar et al., 2024).
- "*Limit the increase in resource consumption compared to the increase of GDP*", suggested as a circularity parameter in ISO 59020, applies a meso- or macro-perspective, incompatible with a product- or process-oriented LCA. Measuring this parameter would require additional regional-level data on resource consumption and is, therefore, not a realistic indicator for providing complementary information to optimize the sustainability of a single product or process.

We would argue that these five circularity strategies provide only limited additional information on a product or process's environmental benefits compared to an LCA. Note that some of these five circularity strategies relate to socio-economic concepts, which are, ideally covered in advanced life cycle sustainability assessment frameworks (Valdivia et al., 2021). If these strategies are still relevant in a specific study and they are not covered by an overarching LCSA approach, Circularity Indicators can be used as a complement to an LCA study to address them. The fact that expanding to LCSA will cover more circularity strategies and sustainability implications supports the conclusion of Walzberg et al. (2021): "*Complex systems science methods and further developments of industrial ecology methods (e.g., the development of Life cycle sustainability assessment combining LCA, LCC, and S-LCA) could, therefore, help study the consumption and production side of CE altogether*".

Even though other assessed circularity strategies are covered by at least one LCA approach, combining different LCA approaches to observe a product system from various angles (i.e., different "research questions") may be time-consuming and may lead to misinterpretations of results, as different messages are conveyed in parallel. Therefore, to enhance the evaluation of circularity strategies, we formulated a framework to identify complementary stand-alone circularity indicators that can be employed in tandem with an LCA method selected based on the goal and scope of an LCA study. This integrated approach helps to reveal the potential benefits of specific strategies, ensuring a more holistic assessment.

We acknowledge that the scope of this paper is limited to the selected LCA methods and Circularity Indicators, resulting in a top-down inclusion of circularity strategies (i.e., circularity strategies were included in this research only if they were mentioned by at least one of the assessed methods). Other circularity strategies may be missing from this assessment, and different combinations of LCA methods and Circularity Indicators may also be feasible. However, the cross-comparison of the identified circularity strategies with the 9R framework (in Supplementary Table 5) showed that all R strategies are covered by our selection, except for the R0 strategy ("Refuse": Make the product redundant by abandoning its function or using a different product.). "Refuse" is out of scope of our analysis, since LCA focuses on existing systems. "Reduce" (increase efficiency by consuming fewer natural resources and materials) and "Recycling" are most often represented by the circularity strategies identified in this paper. The former can be explained by a focus of LCA on impact (reduction), which includes the use of natural resources. The focus on Recycling may be caused by a bias of LCA allocation methods on the modeling of recycling, rather than on remanufacture, refurbish, and repurpose. Overall, the fact that all R's are covered (except R0 "Refuse"), shows that the set of circularity strategies covered in this paper is rather complete, and relevant in a broader context of circularity strategies. Future work may expand on the evaluation in this paper by adding additional methods and considering potentially relevant strategies and attributes, such as the temporal differentiation of processes and emissions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

DS: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. TS: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. MV: Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. MS: Validation, Writing – review & editing. AC: Validation, Writing –

review & editing. MA: Funding acquisition, Validation, Writing – review & editing. EE: Funding acquisition, Project administration, Validation, Writing – review & editing. MG: Validation, Writing – review & editing. TR: Funding acquisition, Validation, Writing – review & editing. NA: Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

DS, MV, and NA were employed by WeLOOP. AC and MA were employed by Neovili. EE and MG were employed by Contactica.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) TS and DS declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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TABLE 1
LCA and CI coverage of circularity attributes and strategies.

DATA SHEET 1
Modeling of circularity in LCA methods and assessment of circularity strategies.

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