



CALiMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D3.3.

Circular economy and criticality assessment methodology definition

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LIST OF ACRONYMS

EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment

GLOSSARY

Term	Definition
Circularity aspect	Element of an organization's activities or solutions that interacts with the circular economy
Circularity assessment	Evaluation and interpretation of results and impacts from a circularity measurement. Assessment includes consideration of the sustainability aspects and can apply complementary methods such as life cycle assessment
Circularity economy	Economic system that used a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development
Circularity indicator	Metric used to measure one or more circularity aspects. A circularity indicator can represent a measurable aspect or combination of aspects of a resource, a solution, process or action
Circularity measurement	Process to help determine the circularity performance through collection, calculation or compilation of data or information
Circularity performance	Degree to which a set of circularity aspects align with the objectives and principles for a circular economy
Complementary method	Method, approach or standard that is used together with circularity measurement to provide a circularity assessment
Qualitative indicator	Measure derived from a checklist or descriptive scale without any quantification. Qualitative indicators can be categorized into classes that can be assigned numeric values

Quantitative indicator	Measure based on numeric data that can be used for mathematical calculations and statistical analysis. Quantitative input data are based on physical or economic unit of measurement
Resource	Asset from which a solution is created or implemented. Depending on the context, reference to “resource” includes “raw material”, “feedstock”, “material” or “component”. Resource also includes any energy type and can be considered concerning both stocks and flows
Waste	Resource that is no longer considered to be an asset as it, at the time, provides insufficient value to the holder. Value can be assigned to waste as a result of a need from another interested party, at which point the resource is no longer considered waste

Source: ISO 59004:2024, Circular economy – vocabulary, principles and guidance for implementation

PROJECT INFORMATION

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8	Technical University of Denmark DTU
9	Techtera TECHTERA
10	Essity ESSITY
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DELIVERABLE DETAILS

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Abstract:	The increasing demand for sustainable practices in the bioeconomy context has driven the integration of circularity aspects and criticality indicators within Life Cycle Sustainability Assessment (LCSA) methodologies. This study, part of the CALIMERO project, investigates strategies to address sustainability gaps and improve resource efficiency in bio-based sectors, including construction, woodworking, biochemicals textile, pulp and paper and woodworking. The D 3.3 report evaluates circularity indicators across the EU and modelling multi-life cycle inventory flows, the research seeks to reduce environmental impacts and enhance the sustainability of bio-based products. Additionally, a comprehensive criticality assessment highlights the challenges and synergies between circular economy actions and the criticality of bio-based materials, with a particular focus on wood, identified as a potentially critical resource in the EU. The analysis employs frameworks such as the BIRD methodology and indicators from Schrijvers et al. to address supply risks, data limitations, and mitigation measures. This report delivers actionable recommendations for incorporating these interconnected frameworks into LCSA, promoting resilience and sustainability across bio-based industries.

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1 INTRODUCTION

1.1 Context

The concepts of circularity and criticality are gaining prominence in both academic research and policy-making as the global demand for raw materials intensifies. Recognizing the growing importance of these issues, the European Commission (EC) has played a central role in addressing these issues. Since 2010, the EC has published a triennial assessment of critical raw materials (CRMs); with the most recent list in 2023 identifying 34 materials as critical to the European economy (European commission, 2010; 2023a). Complementing this, the Critical Raw Materials Act (CRMA) further outlines actions aimed at ensuring secure and sustainable supply chains within the European Union (EU), supported by complementary regulations (European Commission, 2023b). Simultaneously, the EC's Circular Economy Action Plan, a pillar of the European Green Deal, underscores the EU's commitment to sustainable growth and resource management (Gursel et al., 2023; Hackenhaar et al., 2024).

Circularity and criticality are inherently interconnected. Actions leading to a more circular economy, such as those outlined on the 10 Rs hierarchy, listed by Reike et al., (2018) - *refuse, reduce, resell/reuse, repair, refurbish, remanufacture, repurpose/rethink, recycle, recover, and remine* – can simultaneously reduce dependency on external supply chains and mitigate the criticality of raw materials in the EU. This synergy is explicitly recognized within the CRMA's strategic priorities. However, it is noteworthy that the most effective actions, such as refusing and reducing resource consumption, are often excluded from the conventional product-centric scope of Life Cycle Sustainability Assessments (LCSA). Addressing this gap requires alternative frameworks to evaluate and promote these strategies. Conversely, integrating other circularity strategies into LCSA can assess their dual benefits: enhancing material circularity while improving environmental performance (Andersen et al., 2022). At the same time, criticality assessments can play a complementary role in guiding circular economy strategies by identifying priority materials for targeted interventions. Both frameworks emphasize the importance of resource efficiency, resilience, and sustainability, making their integration particularly valuable in the context of the bioeconomy. Circularity can also directly influence criticality by reducing the dependency on materials with high criticality ratings (Hackenhaar et al., 2024).

In this report, we propose that circularity should be accounted for both as a general performance indicator and within the modelling of LCSA, incorporating the environmental, social and economic impacts of circular economy actions. For example, the effects of recycling could be reflected in the allocation of life cycle inventory (LCI) flows and their associated environmental impacts. Criticality, on the other hand, can serve as an additional tool within the interplay between circularity and criticality across five bio-based sectors- pulp and paper, construction, biochemicals, woodworking, and textiles – highlighting the synergies, challenges, and opportunities for integrating these concepts into sustainable resource management.

1.2 Aim and objectives

The main objectives for Task 3.2 within the CALIMERO project are:

- (i) Integrating circularity aspects in LCSA by:
 - (a) Investigating circularity strategies to address sustainability gaps in bio-based sectors
 - (b) Evaluating allocation of inventory flows across multiple life cycles using different methodologies
 - (c) Assessing the applicability of circularity indicators from various EU initiatives
- (ii) Incorporate criticality indicators for bio-based materials by:
 - (a) Conducting a criticality screening for raw materials, focusing on wood as a critical raw material in the EU context

- (b) Evaluating the relevant of criticality indicators for bio-based materials
- (c) Assessing data availability for indicator evaluation and providing recommendations for criticality awareness and mitigation strategies.

1.3 Report structure

Following this introduction, the report is structured in two different parts as follows: Part I focused on the incorporation of criticality indicators in the context of bio-based materials, and Part II focused on the integration of circularity aspects in LCSA.

PART I - CRITICALITY

2 INTRODUCTION

The supply chains of the products that we use are getting increasingly complex, some raw materials or components are distributed around the globe before ending up in a final product at the consumer. The increased globalisation of supply chains has as a consequence that countries are dependent on trade with one another for access to raw materials or semi-finished products, which can be considered as a factor of **supply risk**.

The relevance of supply risks has been broadly acknowledged in the supply chains of metals and the technologies in which they are used, such as electric mobility, renewable energy, the IT (Information Technology) sector, or aerospace, to name a few. The supply risk of raw materials can be assessed via a **raw material criticality assessment**.

Raw material criticality assessments assess the likelihood of a supply disruption of a raw material to a system (e.g. a company or a national economy), and the vulnerability of this system to such a supply disruption, in line with a classical “risk” assessment (Glöser et al. 2015). A typical reason that a raw material can be considered “critical” is that production is concentrated in a single country, where the risk could be higher if this country is associated with poor governance. Other factors of concern are strong demand increases due to technology shifts, as seen in the mobility sector, or high environmental impacts or social concerns (such as child labour or the violation of human rights) within the value chain (Schrijvers et al. 2020b). These aspects do not only potentially affect the **accessibility** to raw materials – they may also lead to **strong price increases** or potential **reputation damage** (Schrijvers et al. 2020a; IRTC 2023). Reputation damage is included as a risk factor, as under extended producer responsibility frameworks, organizations must report on mitigating environmental, social, and human rights risks, particularly when media allegations highlight harmful practices. Potential reputation damage as a “risk” actually increases the scope of criticality assessment from “supply risk” to “value chain risk” (Schrijvers et al. *in preparation*). However, for ease of reading, the term “supply risk” will be maintained in this report.

Common awareness is increasing that not only metals may be critical, but also other types of raw materials and products – such as drugs and medical equipment, as experienced during the COVID-19 pandemic. However, the **bio-based sector** has only played a minor role in published criticality assessments (Schrijvers et al. 2020b).

Also, in bio-based industries, “criticality” refers to the assessment of how the failure or disruption of a component within an integrated system can impact the overall system's performance. This concept is fundamental for understanding and managing risks in systems where components are highly interdependent, such as bioenergy-based industrial symbiosis networks. By using criticality indices, bio-based industries can prioritize risk management efforts and improve system resilience, particularly in the face of external disruptions

like climate change. (Benjamin et al. 2015, 2017) advanced a rationale for the criticality index as a measure used to quantify the impact of a component's failure on the system's output. It is defined as the ratio of the fractional change in the net output to the fractional change in the capacity of the component causing the failure. This index helps in ranking components based on their risk to the system, aiding in risk management and policy development (Benjamin et al. 2015, 2017). The criticality index also develops risk management strategies to protect critical facilities within integrated bioenergy systems. This is particularly important in mitigating the effects of disruptions, such as those caused by climate change, which can affect biomass feedstock availability (Benjamin et al. 2017). Finally, by understanding criticality, bio-based industries can enhance the robustness of their systems against disruptions, ensuring more reliable and sustainable operations (Benjamin et al. 2017).

The European Commission prepares every three years a list of raw materials that are critical for the European economy, based on an evaluation of 70 raw materials, including metals, industrial and construction minerals, and biotic materials (natural rubber, natural cork, roundwood, sapele wood, and natural teak wood). Whereas none of these biotic materials were considered “critical” in the 2023 evaluation (fifth list) (European Commission 2023a), the number of supply-risk indicators considered in the assessment and the coverage of the entire bio-based sector is limited. Moreover, the classification by EC is a yes-or-no classification, using a threshold, whereas in criticality could be considered as a spectrum. The results of the EU study may give the impression that criticality is evaluated in a comprehensive manner, although there are multiple limitations that must be acknowledged. More lenient approaches could provide new and other insights.

Does that mean that the concept of raw material criticality is of less relevance to the bio-based sector? Or does the concept of “criticality” mean something different for bio-based materials, compared to metals?

Several topics emphasize the relevance of the concept for the bio-based sector. Below are a selection of aspects that highlight the criticality of being relevant for the biobased sector (Bach et al. 2017a):

- 1- Primary forests and their age of more than 500 years or even 1000 years, which can therefore not be considered as “renewable”, and which may risk being depleted,
- 2- Environmental and biodiversity impacts caused by deforestation to produce bio-based materials,
- 3- Arable land as a competitive resource with access to land for crops and geopolitical tensions related to land,
- 4- Competition of demand and limited offer (e.g. of food versus fuel, etc.)
- 5- Low renewability of biomass-based stocks, i.e. it takes time to grow biomass.

In the EU study, the bio-based materials are evaluated via the same set of indicators as the metals. Other studies that evaluate the criticality of bio-based materials exist as well, such as a criticality study on construction wood based on a framework initially applied to metals (Ioannidou et al. 2019), and the BIRD methodology that uses a unique set of indicators to evaluate the criticality of bio-based materials (Bach et al. 2017a). Up to now, it is unclear whether a common criticality methodology and corresponding data sources can be applied to evaluate the criticality of metals and bio-based resources, or whether distinct methodologies are necessary (Rietveld and Bastein 2019).

3 GAPS IN CRITICALITY ASSESSMENT METHODOLOGIES

In task 1.3 of the CALIMERO project, we investigated, among other gaps, the topics of criticality in LCSA. In section 3 below, we summarize key points regarding the gaps for the accounting for criticality in the LCSA framework.

Table 1. Overview of Key Gaps in Accounting for Criticality within the LCSA Framework.

N°	Type of gap	Gap	Possible solution(s)	Coverage in this deliverable
1	Conceptual	<i>Criticality in general</i> Conceptual understanding of role of criticality: "What does one seek to evaluate in terms of criticality in general and in the context of an LCSA specifically?"	Development of impact pathways that connect inventory flows, via criticality indicators, to end-point categories	Not addressed
2	Conceptual	<i>Criticality in general</i> How does criticality fit in the framework of LCA, S-LCA, and LCC?	From the previous solution, the suitable end-point category can be fitted into an LCSA framework	Not addressed
3	Modelling	<i>Criticality in general</i> Unclear whether the economic pillar should be based on ISO 14040, which applies a natural science approach	Based on the solution of gap #1, it can be identified to what extent a criticality assessment can and should be aligned with ISO 14040 and to what extent it deviates, and how such a deviation affects the practical application and interpretation of criticality assessment results	Not addressed
4	Modelling	<i>Criticality in general</i> Limited coverage of intermediate flows inside the criticality model, including recycled materials and auxiliary products	The need to cover both elementary and intermediate flows will be emphasized at a conceptual level. Data gaps regarding intermediate flows will be clarified.	Addressed
5	Modelling	<i>Criticality in general</i> Limited coverage of different types of scopes (global, country, company...)	The formulation of a goal and scope and identification of different economic stakeholders will be clarified in the development of use cases that illustrate the application and interpretation of a criticality assessment in the context of LCSA	Addressed

6	Modelling	<i>Criticality in general</i>	Limited consideration of supply-risk factors	The IRTC model as applied in IRTC (2023) (containing numerous criticality indicators applied to metals) is complemented with supply-risk factors from the BIRD method	Addressed
7	Modelling	<i>Criticality in general</i>	Limited consideration of criticality mitigation measures	Mitigation measures are matched with a criticality impact pathway in the IRTC model	Addressed
8	Modelling	<i>Criticality in general</i>	Limited validation of criticality indicators based on empirical evidence	Survey among companies on how (economic) events affected their accessibility to raw materials (out of scope of this study)	Not addressed
9	Modelling	<i>Criticality in general</i>	Definition of impact pathway of criticality in LCSA	Combining the impact pathways of the IRTC model, GeoPolRisk, SPOTTER, and the framework of Neugebauer for economic sustainability assessment	Partly addressed
10	Modelling	<i>Criticality in general</i>	Arbitrary selection of critical vs non-critical materials (e.g. via threshold value or targets based on surveys.	The need to determine a criticality threshold value will be clarified in the development of use cases that illustrate the application and interpretation of a criticality assessment in the context of LCSA	Addressed
11	Modelling	<i>Criticality in general</i>	Addressing uncertainties due to LCIA modelling data	Data ranges may be calculated, for example based on the pedigree matrix of Weidema and Wesnæs (1996)	Partly addressed
12	Modelling	<i>Criticality for bioeconomy</i>	To what extent different criticality modelling methods should be applied to bio-based materials (compared to metals)	Matching of the IRTC criticality model (which contains a comprehensive set of criticality indicators applied to metals) with the BIRD method, which is a specific assessment method for bio-based materials, to identify complementarity. The	Addressed

				final set of indicators will be tested on their applicability to the bioeconomy	
13	Data	<i>Criticality in general</i>	Need for evaluation of elementary + intermediate flows (instead of only elementary flows in environmental LCA)	The need to cover both elementary and intermediate flows will be emphasized at a conceptual level. Data gaps regarding intermediate flows will be clarified	Addressed
14	Data	<i>Criticality for bioeconomy</i>	Access of companies and sectorial stakeholders to relevant data to evaluate the criticality of biobased materials	Once it is evaluated whether the biobased sectors can and should evaluate critical raw materials via the same or different indicators than metals, a screening of potential data sources will be conducted, resulting in an identification of data gaps	Addressed

4 INTRODUCTION TO THE IRTC PROJECT

The International Round Table on Materials Criticality (IRTC) is an international network of experts in Critical Raw Materials (CRMs). The first phase of the project (2018 – 2020) laid the cornerstone for a long-lasting international network via the organization of Round Table discussions at international conferences around the topics “How methodology determines what is critical”, “Criticality and the Circular Economy”, and “How Industry Manages Criticality”. These discussions brought forth several joint publications (e.g. (Schrijvers et al. 2020a, c; Tercero Espinoza et al. 2020; Hool et al. 2022; Cimprich et al. 2023)), presenting research on differences and commonalities of different approaches on criticality, as well as implications for industries, policymakers, and circular economy. In 2020, the IRTC project put an increased focus on supporting industries in the identification and managing of CRMs, via (virtual) round table discussions and workshops with the support of an Industry Focus group, the publication of guidance documents, and the development of a web-tool (IRTC 2023).

The concept of criticality has gained interest in the past decade in the LCA community. Several methods have been developed (e.g. GeoPolRisk (Gemechu et al. 2017; Cimprich et al. 2019), ESSENZ (Bach et al. 2016), ESP (Schneider et al. 2014), and SPOTTER (Berr et al. 2022)), and criticality is often considered as a relevant tool in an LCSA toolbox or methodology. Although the focus of the IRTC project has not been on the assessment in the context of LC(S)A, there has been a desire from the LC(S)A community to align their recommendations with the findings of the IRTC project (Hackenhaar et al. 2022).

5 ILLUSTRATIVE EXAMPLE

In this report, conducting a criticality assessment for a case study in the bioeconomy is illustrated via an example case study. The case study represents the production of Laminated Strand Lumber (LSL) in the Spanish woodworking sector. LSL is produced from low-quality wood scraps from the poplar forestry sector in Spain (Figure 1). In this specific case, no chemicals are used in the forestry activities. Steam used during drying and screening of the chipped wood is provided from incineration of biomass, including both virgin sawdust (from pine and beech wood) and waste biomass from the process (including discarded chips, dust, trimmings and board waste). In this illustrative case, it is assumed that LSL is used in the European construction sector.

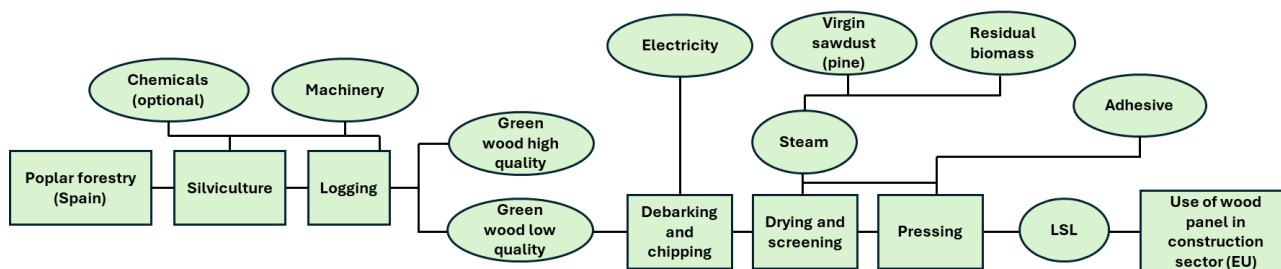


Figure 1. Schematic representation of the cradle-to-gate value chain of the production of Laminated Strand Lumber (LSL) as introduced in Deliverable 2.1 of the CALIMERO project.

6 CONDUCTING A CRITICALITY ASSESSMENT FOR THE BIOECONOMY

There is no standardized way to conduct a criticality assessment. Schrijvers et al (2020b) observed that the design of a criticality assessment is strongly dependent on the goal and scope definition, similar to LCA. Therefore, based on the similarities with LCA, a step-by-step framework for conducting a criticality assessment was developed by Helbig et al (2021), presented in Figure 2. In this report, these steps are followed and different modelling choices are highlighted that are prevalent in a case study of the bioeconomy.



Figure 2. Step-by-step guidance for the design and communication of a criticality assessment, with examples of potential methodological choices (Helbig et al. 2021).

6.1 Defining the Goal and Scope

The Goal and Scope definition of a criticality assessment comprises the following steps (see Figure 2):

- Definition of the system at risk
- Definition of the anticipated risk
- Selection of materials and flows that are evaluated
- Formulation of the objective of the assessment

6.1.1 Definition of the system at risk

Schrijvers et al (2020b) noted that a criticality assessment can be conducted from different perspectives, such as a regional economy, an economic sector, a company, or a product system. The “system at risk” is therefore

defined in terms of the applied stakeholder perspective. For example, within the illustrative case presented in Figure 1 several “systems at risk” can be identified that can be the subject of a criticality assessment:

- The European economy
- The European construction sector
- The Spanish woodworking sector
- The Spanish forestry sector
- A specific company that uses LSL
- The company that produces LSL
- The entire product system of LSL

At every system level, value is provided to (a) geographical area(s) related to the system in the form of jobs created, local goods (including goods that contribute to environmental sustainability, such as low-carbon energy technologies) and local revenue (incl. salaries and taxes), which is at potential risk due to supply disruptions. Therefore, at each step in the value chain, there is a potential contribution to “local prosperity” (which is considered as an end-point indicator in the economic pillar of LCSA by (Neugebauer et al. 2016)) at various geographic areas, as illustrated in Figure 3. For example, the EU study on critical raw materials considers the European economy as “system at risk”, focusing on value added to the European economy. Criticality assessment methods developed for use in LC(S)A may vary in the considered “system at risk”. For example, the SPOTTER method (Berr et al. 2022) seems to apply the perspective of the “global economy”, considering the risk of losing global prosperity due to supply disruptions (see Figure 3). This has implications on the accepted levels of substitutability (i.e. possible substitution of one supplied good by another), which is commonly considered as a criticality-mitigating factor (Schrijvers et al. 2020b), such as at a raw material level, product level, or functionality level. At the same time, companies are increasingly interested in the implementation of “supply risk methods” in the LCSA framework, although it is doubtful whether the general LCSA global scope is appropriate to accommodate this stakeholder-specific interest.

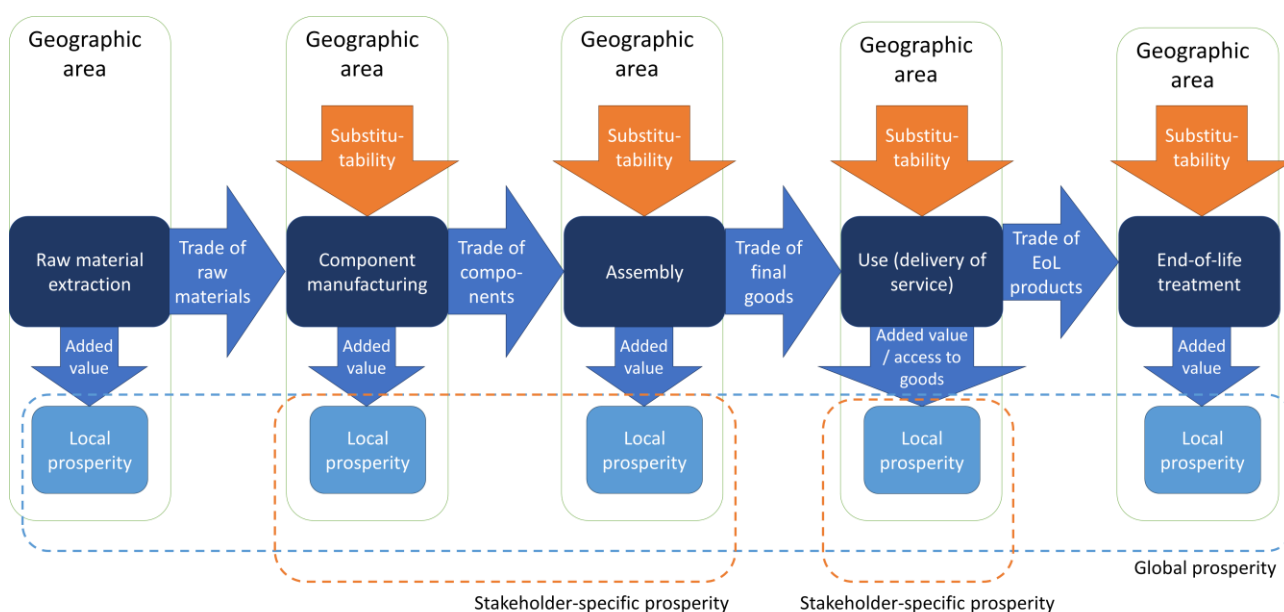


Figure 3. Comparison of scopes of Raw Material Criticality Assessments (focusing on stakeholder-specific prosperity) with LCSA (focusing on global prosperity).

For illustrative purposes, for this example, the “system at risk” is formulated as **the system that produces LSL**, i.e. a company. The system boundaries of this system are drawn in Figure 4.

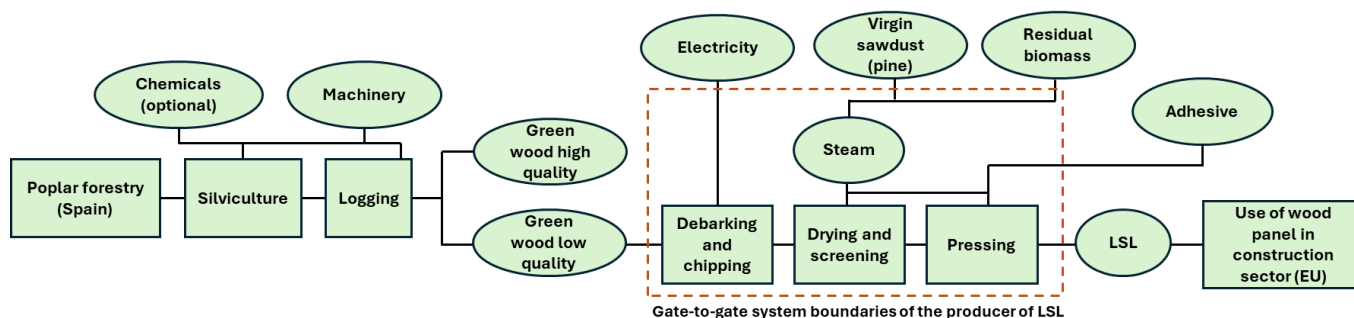


Figure 4. Gate-to-gate system boundaries of the company that produces LSL, here identified as “the system at risk”.

6.1.2 Definition of the anticipated risk

Although “supply risk” is often strongly associated with problems with accessing a raw material, the IRTC project identified three types of risks that are generally anticipated by companies (Schrijvers et al. 2020a):

- Accessibility problems
- Strong and unexpected price fluctuations
- Reputation damage

Criticality methods vary in the extent to which these risk types are considered. For example, the GeoPolRisk method (Santillán-Saldivar et al. 2022) focuses on the risk of price increases. Alternatively, Bach et al. (2017) developed the BIRD methodology that uses a unique set of indicators to evaluate the criticality of bio-based materials (Bach et al. 2017b). The BIRD method considers both accessibility problems and potential reputation damage. In this report, all three types of risks are considered.

A cause-and-effect diagram was developed within the IRTC project (Figure 5) to illustrate the potential consequences of these three “risk types” on a company, and subsequently on the (local) economic system (e.g. loss of access to goods (which could be further specified as specific types of goods, such as renewable energy technologies), loss of jobs, and loss of revenue from taxes). In the Calimero report, besides the provision of “taxes” we consider the provision of “revenue”. Revenue includes salaries (providing purchasing power to the local population), investment options (in OPEX and CAPEX), profit, and taxes, all contributing to local prosperity.

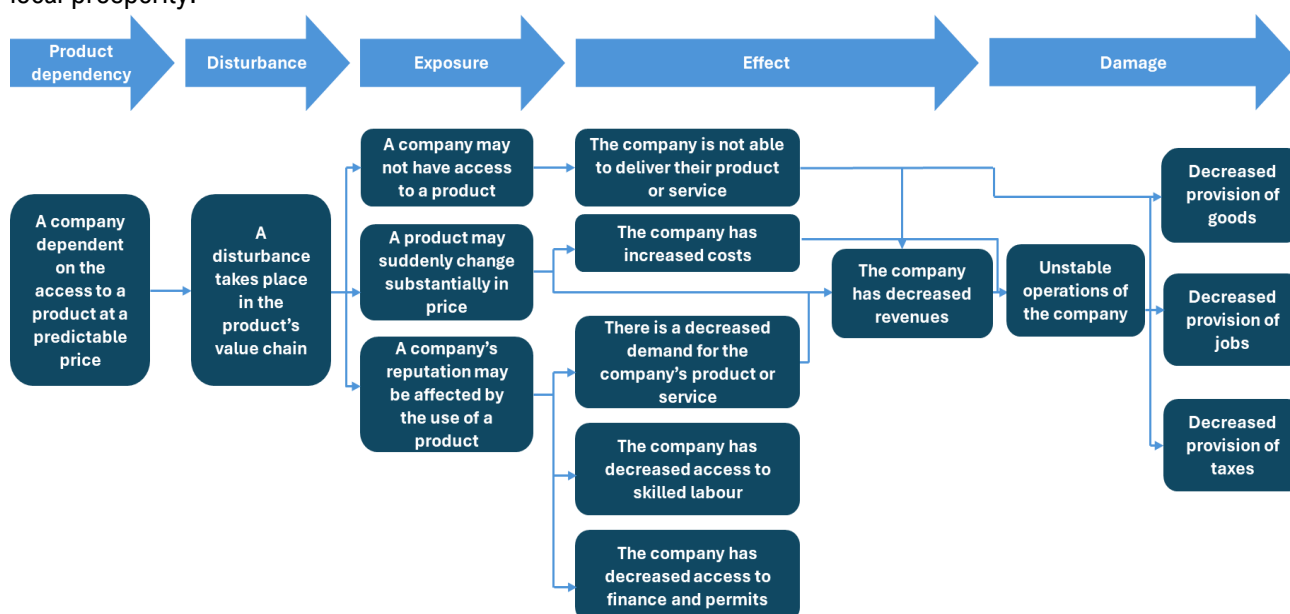


Figure 5. Establishment of a cause-and-effect chain for the qualitative evaluation of potential damage on local prosperity via a raw material criticality assessment (Schrijvers et al, forthcoming).

6.1.3 Selection of materials and flows that are evaluated

An ideal criticality study considers all raw materials, components, and final products used by the system at risk at all stages of the value chain that may be subjected to supply risks. However, in practice often a narrower selection of raw materials is applied, due to practical limitations or a selected focus. Most criticality studies have had a focus on minerals and metals, and, due to lacking information on (trade) flows downstream in the supply chain, often only the mining and refining stages are considered.

For the assessment of supply risks for the bioeconomy, it is relevant to distinguish between biotic resources, abiotic resources, and man-made biotic materials (Bach et al. 2017b). Bach et al (2017) refer to biotic resources as objects derived from living entities¹ extracted from the ecosphere (i.e. produced by natural processes, not by industrial processes or economic activities). Man-made biotic materials are objects derived from living entities extracted from the Technosphere, for example in agricultural or forestry activities. “Biotic materials” comprise both biotic resources and man-made biotic materials (Bach et al. 2017b). Furthermore, the production of man-made biotic materials may rely on the availability of abiotic resources, such as land and phosphorous, but also metallic raw materials such as materials used for machinery, or for the production of energy technologies that provide electricity and heat to the system. In Annex 1, the relevance of criticality indicators for each specific category of flows within the bioeconomy is highlighted.

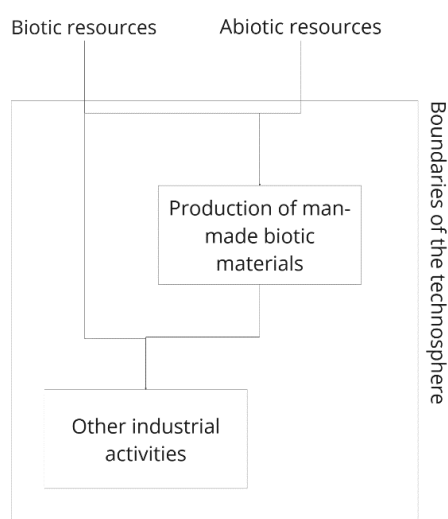


Figure 6. Distinction between biotic resources, abiotic resources, and man-made biotic materials according to Bach et al. (2017).

However, the relevant flows for a criticality assessment of a bio-based value chain are not limited to biotic materials. For example, from the perspective of the producer of LSL, the following incoming flows may be subject to disruptions in the supply chain, resulting in difficulties for the LSL producer to access the respective flow, strong fluctuations in price, or potential reputation damage due to the use of the flow:

- Low-quality green wood
- Electricity
- Virgin sawdust (pine and beech wood)
- Waste biomass (discarded chips, dust, trimmings, and board waste)
- Adhesive material (in this case a polymeric methylene diphenyl diisocyanate glue, in some other cases formaldehyde-based adhesive is used)

¹ Rephrased as “objects derived from living entities” instead of “living objects” in the original source.

Ideally, the potential supply risks related to these flows are assessed at each step in the upstream value chain. For example, it could be considered that the access to low-quality green wood is directly disrupted, or that the producers of green wood experience supply risks themselves, for example regarding the required machinery to harvest the greenwood.

In most criticality studies targeting metals and minerals, supply disruptions are only assessed at the raw material extraction or refining step. This is due to the availability of data on these value-chain steps, whereas data on downstream component manufacturing is less widely collected. However, several supply risk factors may intervene anywhere in the value chain, such as monopoly positions of component manufacturers, reliance on by-products at downstream processing stages, or natural disasters taking place at sites where final products are produced.

In this report, it is recommended to consider by default all intermediate products used by the “system at risk”, and to consider potential supply disruptions at all upstream stages of the value chain. If this selection of intermediate flows is too large, the choice can be narrowed down by the following steps:

1. Identify which activities generate (most) added value to the “system at risk” under study. This may be evaluated by a (collection of) Life Cycle Costing studies. In the illustrative example, the activity is already limited to the production of LSL from low-quality green wood.
2. Assess the stakeholder’s vulnerability to a supply disruption
 - Accessibility problems: Identify for which intermediate products a lack of access will impede the potential to deliver the company’s product or service.
 - Price fluctuations: Identify for which intermediate products a change in price will most impact the company’s profitability. This can be assessed by, for example, a breakdown of the company’s CAPEX and OPEX, to identify the main contributors to costs, considering also maintenance and replacement of required equipment.
 - Reputation risks: Conduct a screening LCA and Social LCA to identify the main environmental and social hotspots in the product’s value chain.
3. Identify intermediate flows for which risk mitigation strategies are already in place. For this, the mitigation measures as suggested in the IRTC tool (IRTC 2023) may be considered. For example, intermediate flows may be excluded from the initial analysis in the following cases (non-exhaustive):
 - The intermediate flows are easily substitutable (e.g. using steam from natural gas rather than steam from biomass residues)
 - The intermediate flow already has a high End-of-Life (EoL) recycling input rate
 - Certification schemes are already in place for the intermediate flow

6.1.4 Definition of the objective of the assessment

Potential objectives of a criticality assessment are, according to Helbig et al. (2021), to make policy decisions, to inform on required mitigation strategies, to conduct a screening for a more in-depth study, or to identify hotspots in the value chain. The EU list of CRMs is established with (among others) the objective to make policy decisions. This requires a clear distinction between critical and non-critical raw materials, i.e. based on a threshold value which is often criticized in the scientific literature (Hackenhaar et al. 2022). In a company-oriented context, it may be sufficient to identify criticality hotspots and identify options for mitigation measures. In that case, criticality scoring per indicator may provide enough information, and indicators may not need to be further aggregated. Furthermore, there is more room to consider the uncertainty of the data.

6.2 Select and evaluate indicators

In this chapter, an assessment framework is developed that allows for the criticality evaluation of both biobased materials and minerals and metals.

6.2.1 Indicators for the bioeconomy

From a review of about 40 criticality assessment studies, Schrijvers et al. (2020b) established a list of indicators that are commonly used to assess the criticality of minerals and metals. Specific studies do not always justify their indicator selection, which makes it difficult for new method developers to choose between the numerous available indicators for a new criticality study.

Schrijvers et al. (2020b) argued that indicator selection is based on the anticipated risks identified/selected by the method developers. This requires a clarification of the cause-and-effect chain of criticality indicators, i.e. to understand which criticality aspect each indicator tries to measure, and how this contributes to one of the three above-mentioned anticipated risks. Within the IRTC project, impact pathways have been established that link the commonly used criticality indicators to these anticipated risks. The linking of indicators to the anticipated risks is done by the creation of “storylines” that aim to reflect the logical thinking behind the selection of certain indicators (Figure 7). Unlike in environmental LCA, where impact pathways are quantified via characterisation factors, these storylines are not quantified but focus on the *relevance* of inclusion or exclusion of a specific indicator.

The full list of indicators used to quantify each supply-risk factor included in Figure 7 is given in Annex 1. The indicators included within the IRTC model have been quantified for around 50 metals and minerals, and the indicator scoring is integrated into a freely accessible webtool (IRTC 2023).

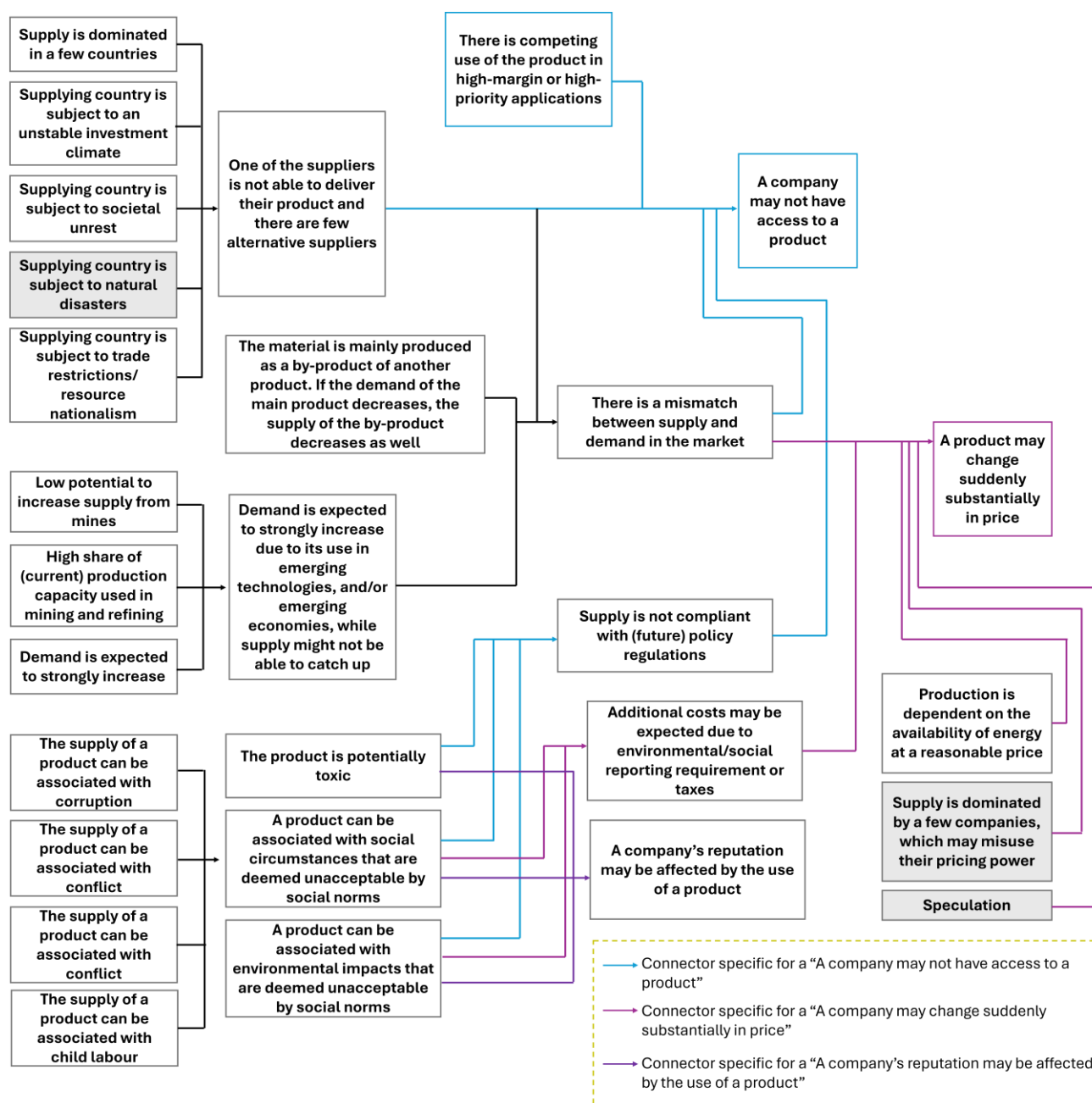


Figure 7. Linking supply risk aspects to company-level risks through storylines within the IRTC project (Schrijvers et al., forthcoming). Grey boxes are not quantified in the IRTC Decision Tool.

Whereas the IRTC framework has been developed for application to metals and minerals, other publications have been published with a focus on the bioeconomy. It can be observed that there is a partial overlap between indicators for metals and for biobased materials, but biobased materials are also subject to supply risk aspects that are not directly relevant for metals, such as the accessibility to land and water, and their renewability rate.

The IRTC framework is here further expanded with methodological insights from the works of Bach et al. (2017) and Ioannidou et al. (2019), who developed criticality assessment method for biobased materials in general, and for wood in particular, respectively.

6.2.1.1 *The BIRD method*

Bach et al. (2017) developed a criticality assessment method for terrestrial biotic materials over the entire supply chain. They investigated five types of constraints (i.e. potential sources of a supply disruption):

- Physical
- Socio-economic
- Abiotic
- Social
- Environmental

Each of these types of constraints is assessed by a number of criticality indicators (Figure 8). However, unlike the IRTC framework, no cause-and-effect mechanisms are developed. Therefore, the criticality indicators are only categorized based on their indicator type, but not on the type of risk they may pose on an economic entity (such as a company).

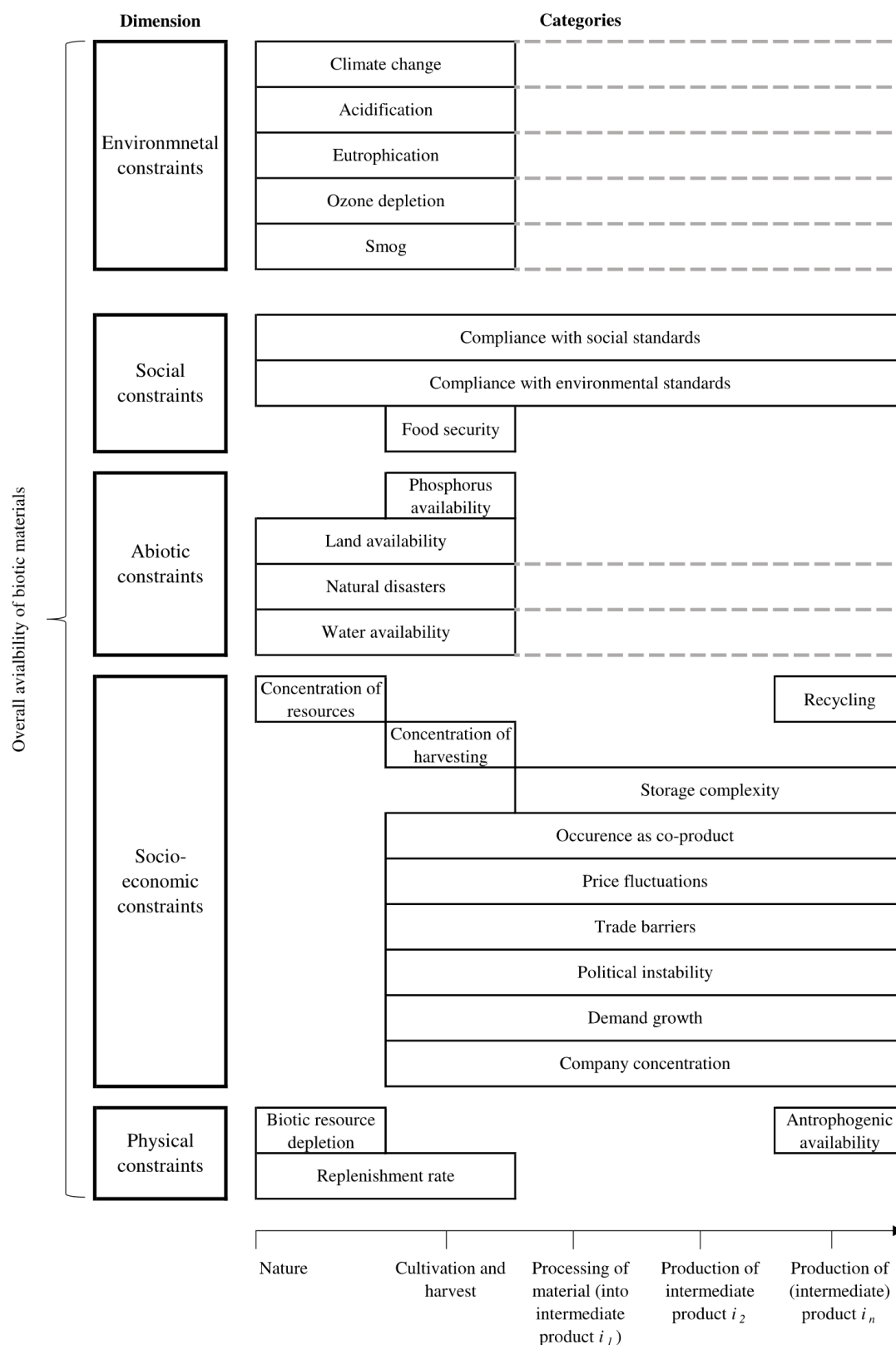


Figure 8. Overview of dimensions and categories influencing the availability of biotic materials and (intermediate) products and the relevant stages of the supply chain (Bach et al. 2017b).

Based on the argumentation for the inclusion of an indicator in the BIRD methodology of Bach et al. (2017), the criticality indicators are integrated into the IRTC framework. First, the supply-risk aspects added by Bach et

al. (2017) are integrated in the cause-and-effect diagram of the IRTC project (Figure 9). Secondly, indicators that are used to quantify these supply-risk aspects are added to the overview of risk indicators in Figure 9.

To facilitate this integration, the following adaptations have been made in the CALIMERO project:

- The Economic Vulnerability Indicator (EVI) is used by Bach et al. (2017) to reflect that a country that stores biotic materials (e.g. as a supplying country or for intermediate logistics) is (not) able to absorb and overcome severe shocks while supporting strong economic growth. The link between the EVI and the ability to handle storage systems is not made very clear by Bach et al. (2017). This effect is arguably also reflected by indicators used for political instability (i.e. the Worldwide Governance Indicators), and could be considered to reflect the risk that the supplying country is subject to an unstable investment climate, as included in the IRTC model. Therefore, in the updated model, the EVI is linked to the risk of an unstable investment climate, which contributes to potential storage risks.
- The considered EVI is comprised of eight indicators, four related to economic shocks and four related to environmental shocks, each contributing equally to the overall score. The economic shock indicators include share of agriculture, fisheries and forestry in GDP, remoteness and landlockedness, merchandise export concentration and export instability. The environmental shock indicators include the share of population living in low-elevated coastal zones, share of population living in drylands, agricultural production instability and the number of disaster victims. The final EVI score for a country is determined by taking the simple arithmetic average of the index scores, ensuring a balanced representation of economic and environmental vulnerabilities.
- Price volatility is included in BIRD as an indicator for socio-economic constraints. This indicator is not included in the final criticality model, as it does not distinguish between expected volatility (due to production cycles and seasonal variability, which is generally anticipated) and unexpected volatility. Furthermore, it is already considered that unexpected price volatility is represented by other aspects, such as market shortages. In the updated model we therefore only assess factors that could *result* in unexpected volatility, rather than using the volatility itself as an indicator.
- There may be an overlap between the indicators that reflect difficulties with extraction of materials from anthropogenic resources and primary material use. However, both indicators are maintained, as data availability may be distinct.
- Bach et al. (2017) consider that a biotic material may be reliant on several resources, such as phosphorous, land, and water.
 - o Land use is assessed by the quantity of land needed. We consider this as an intermediate vulnerability assessment of the biobased system to potential disruptions in land requirements. If land use is relatively high, it is recommended to conduct an additional criticality assessment on potential disruptions to access to land, such as developed by Ioannidou et al. (2019) and Deteix et al. (2023).
 - o For water use, the Water Depletion Index may be replaced by the more recent AWARE method, which is more state-of-the-art to assess the stress on water use in different regions, and which is also included as a water use impact category in the PEF (Product Environmental Footprint) method.
- Environmental impacts caused by the cultivation, extraction, and use of biobased materials (assessed for climate change, acidification, eutrophication, ozone depletion and photochemical ozone formation) are considered by Bach et al. (2017) to negatively impact the successful and efficient cultivation of these species. However, the link between the impacts directly attributed or caused by the bio-based production system and the effects these impacts have on their own cultivation may be weak. Impacts

caused by these production steps may affect product systems in different regions (such as may be the case for climate change), whereas impacts caused by other product systems (e.g. the combustion of fossil fuels) may affect the cultivation of bio-based materials. Therefore, in the updated model, the direct impacts caused by the bio-based system are linked to regulatory and reputation risks, whereas the potential effect of environmental impacts on the successful cultivation of biobased materials is limited by a country's probability to suffer from floods and droughts. Furthermore, it is recommended to assess the impacts via the PEF emission factors (instead of e.g. CML), due to the strong probability that the PEF framework will be used for future reporting or potential emission reduction schemes.

- To determine the replenishment rate of biotic materials, the rating of low yield and high yield are inversed, as it is considered that a low yield results in a higher risk, instead of a high yield.

The BIRD method contains several aggregation steps, aiming to achieve a final criticality score for specific aspects. In some cases, aggregation is meaningful, such as the aggregation of the extraction rate, the resource stocks, and the replenishment rate of a biotic resource to assess whether the extraction rate decreases the resource stock. However, other aggregation steps do not reflect an underlying rationale, besides providing a weighting factor among different indicators that may reflect a similar type of risk (such as current expected resource depletion and historical resource depletion). In line with the IRTC model, it is preferred to keep multiple indicators reflecting a similar risk type separate, for the potential use in sensitivity analyses.

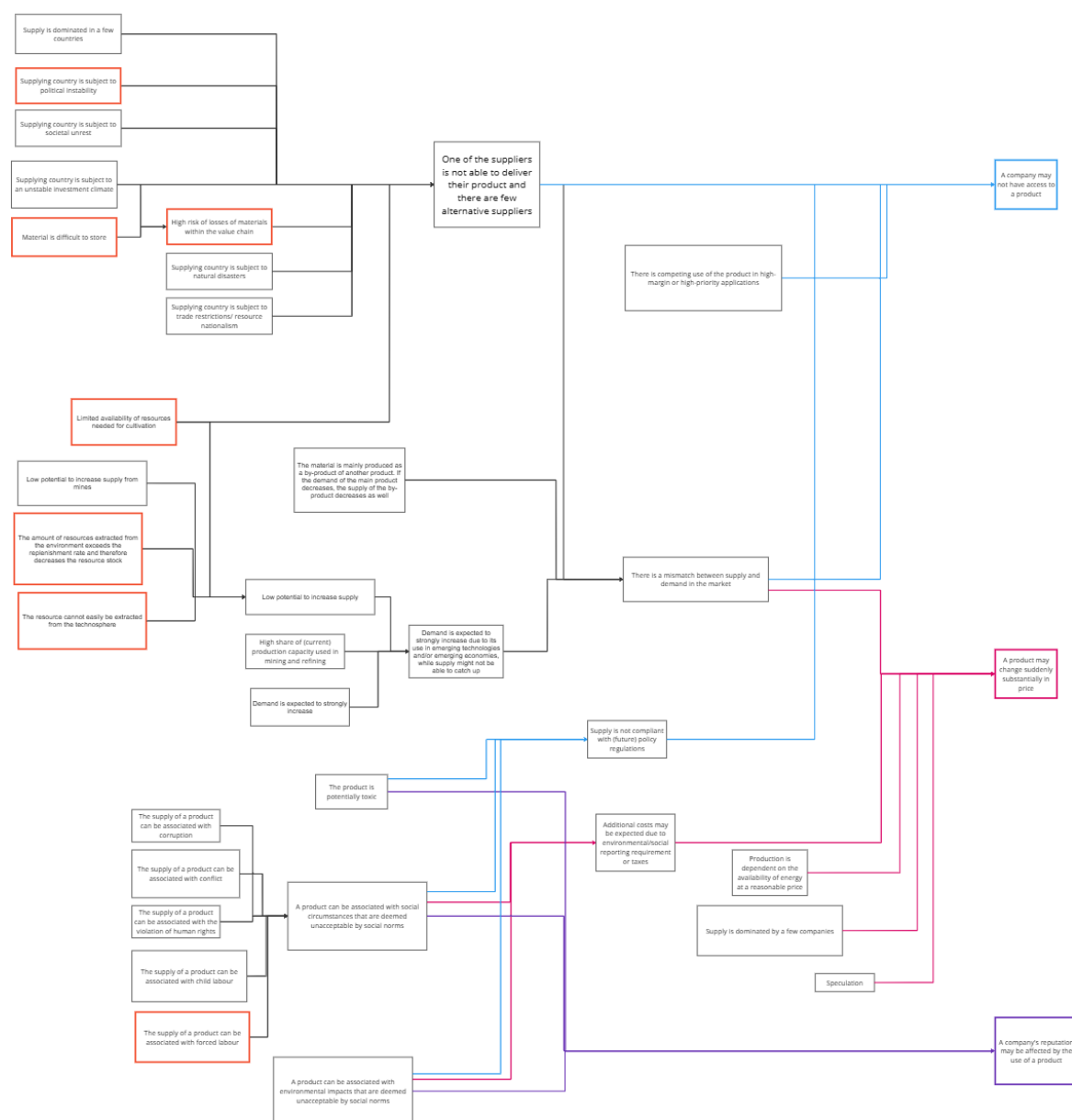


Figure 9. Updated cause-and-effect diagram of the IRTC project including supply-risk aspects relevant for biobased materials (in red), as extracted from the BIRD framework of Bach et al. (2017).

Besides the above-mentioned adaptations to the BIRD method as implemented in this report, the following general limitations of the BIRD method as formulated by Bach et al. (2017) should be noted:

- The availability of aquatic materials is excluded from the method.
- Indicators are developed globally. Supply restrictions are calculated as a global average, and do not highlight individual regions. Therefore, the indicators are proposed as “screening indicators” to determine hotspots. A subsequent study may focus on these hotspots, ideally also applying a more regionalized approach.
- The distinction between “low yield” and “high yield” is challenging and not further developed by the authors.
- Indicator values for a broad range of materials are not easily available, affecting the applicability of the method.

6.2.1.2 Criticality of construction wood systems

Ioannidou et al. (2019) have published a criticality framework for construction wood product systems. Consequently, the indicator selection of biobased materials carried out in the CALIMERO project is complemented by a few additional indicators that have been introduced by Ioannidou et al. (2019). The selection of additional indicators included is based on complementarity to the IRTC and BIRD methods, and general applicability to biobased materials (i.e. not only focusing on wood). The indicators selected from Ioannidou et al. (2019) are also noted in Annex 1.

An overview of selected indicators to quantify the risk sources illustrated in Figure 9 is given in Table 2. In Table 2, a short description of each indicator is provided and more details are given regarding the original use of the indicator, the company risk it contributes to, the relevance for metals and/or biobased materials, the relevance for different steps in the value chain, and potential data sources.

Table 2. Overview of indicators included in the CALIMERO framework, based on the indicator selection from IRTC (Schrijvers et al, in preparation), BIRD (Bach et al. 2017a) and (Ioannidou et al. 2019).

Source of risk	Overview of identified potential indicators
Supply is dominated in a few countries	Concentration of mining countries
	Concentration of biotic resources
	Concentration of harvesting
	Concentration of producing countries of intermediate and final products
	Concentration of refining countries
Material is difficult to store	(Country-dependent) moisture content
Supplying country is subject to an unstable investment climate	WGI – Political stability & absence of Violence/terrorism
	WGI - Government effectiveness
	WGI - Regulatory Quality
	Economic Vulnerability Index
	Economic Vulnerability Index - Share of population living in low elevated coastal zones
	Economic Vulnerability Index - Share of population living in drylands
	Economic Vulnerability Index - Share of agriculture, forestry and fisheries
	Economic Vulnerability Index - Remoteness and landlockedness
	Economic Vulnerability Index - Export instability
	Economic Vulnerability Index - Export concentration
	Economic Vulnerability Index - Agricultural instability
	Economic Vulnerability Index - Victims of disasters (%)
	Fragile States Index
Supplying country is subject to political instability	WGI - Voice and accountability

Source of risk	Overview of identified potential indicators
	WGI – Political stability & absence of Violence/terrorism
	WGI - Government effectiveness
	WGI - Regulatory Quality
	WGI – Rule of law
	WGI – Control of corruption
Supplying country is subject to societal unrest	WGI – Rule of law
	WGI – Political stability & absence of Violence/terrorism
Supplying country is subject to trade restrictions/ resource nationalism	Export restrictions between 2017-2020
	Enabling trade index
Supplying country is subject to natural disasters (Floods and droughts)	Natural disaster risk (NDR) indicator
Supplying country is subject to natural disasters	Disease outbreaks
Limited availability of resources needed for cultivation	Amount of phosphorous applied (kg) in a product system
	Amount of land used (h/year) in a product system
	Water Depletion Index (WDI)
A product can be associated with environmental impacts that are deemed unacceptable by social norms	Cradle-to-gate Life Cycle Assessment
	Climate change
	Acidification
	Eutrophication
	Ozone Depletion
	Photochemical ozone formation
	Environmental Performance Index
	EPI Protected Area Representativeness Index
	EPI Species Habitat Index
	EPI Marine Protected Areas
The supply of a product can be associated with the violation of human rights	EPI Terrestrial Protected Areas
	Human Development Index (HDI)
The supply of a product can be associated with forced labour	WGI – Voice and accountability
	Forced labour per country per sector (SHDB)
The supply of a product can be associated with conflict	Heidelberg Conflict Barometer (not quantified)
	Global Peace Index
	High conflict zones per country per sector (SHDB)
The supply of a product can be associated with corruption	Corruption Perception Index
	WGI – Control of corruption
The supply of a product can be associated with child labour	Child labour (% ages 5-17)
	Child labour per country per sector (SHDB)
The product is potentially toxic	Candidate List of substances of very high concern for Authorisation

Source of risk	Overview of identified potential indicators
The material is mainly produced as a by-product of another product. If the demand of the main product decreases, the supply of the by-product decreases as well	By-product dependency
Demand is expected to strongly increase	Expected demand increase in energy technologies between 2020-2050
	Expected demand increase in emerging technologies between 2020-2040
	Expected demand increase in strategic sectors between 2020-2030
	Production/consumption increase/decrease over the last five years
Low potential to increase supply from mines	Policy Perception Index of countries holding reserves
The amount of resources extracted from the environment exceeds the replenishment rate and therefore decreases the resource stock (biotic resource depletion)	Biotic resource depletion
	Threatened Species Index (TSI)
Biotic resource depletion	Extraction rate
	Resource stocks
	Replenishment rate (biotic resources)
Replenishment rate	Growth rate
	Yield
The resource cannot easily be extracted from the Technosphere	Recyclability
	Replenishment rate (man-made biotic materials)
	Primary material use
Production is dependent on the availability of energy at a reasonable price	Cumulative energy demand
Competing use in high-margin or high-priority products (e.g. health care, strategic sectors, food)	Overview of main uses of raw materials, to be provided in raw material factsheets.
	Food Security Index (FSI)
	Land-use regulation
Supply is dominated by a few companies	Concentration of supplying companies

6.2.2 Data sources and data availability

Potential data sources for each selected indicator are extracted from the IRTC project, the BIRD framework (Bach et al. 2017b) and the work conducted by Ioannidou et al. (2019). As shown in Table 3, ideally, of each intermediate flow, the flow type, suppliers, specific process information, location-specific information, and actor-specific information is gathered. Regarding current suppliers, data may be collected on three different levels:

- Company-specific supply
- Country-specific supply
- Global supply

To assess the supply risks of a specific company, the company-specific supply mix may provide most relevant information on potential supply risks in the very short term. The country-specific (or region-specific) supply mix is applied in several criticality studies, such as the EU list of CRMs (where both global supply and EU import are assessed), and the GeoPolRisk method, where characterisation factors are built for various country import mixes. This country perspective may be valuable to inform policymakers on the potential need to establish geopolitical strategies and trade agreements to protect the local industry. In the IRTC tool, a global perspective is applied. This may provide information on current risks if the full upstream supply chain is unknown (i.e. the upstream suppliers of a company's suppliers are unknown), or to assess the potential to reconfigure supply chains in the case of a disruption.

The recommendation from the CALIMERO project is to collect where possible value-chain specific information (i.e. prioritizing company-specific supply, then country-specific, and finally global supply), and generalize the collected data to a lower level of specification in case of data gaps. Furthermore, country-specific or global supply may be assessed in parallel to company-specific supply, to assess the potential to restructure supply chains.

Table 3. Raw material data collection in an ideal criticality assessment (Schrijvers et al. in preparation).

Collected information for an ideal criticality assessment	Example information
Flow type	E.g. specific type of wood
Flow-specific information	E.g. current suppliers, current and forecasted market users, available reserves
Process-specific information	E.g. specific production technology used, requirement of consumables, emissions to environment, production of co-products
Location-specific information	Regional performance regarding political stability, environmental and social regulations
Actor-specific information	Number of different companies by which the process is operated

Data sources as suggested by the IRTC framework, the BIRD method, and Ioannidou et al. (2019) are provided alongside the corresponding indicators in Annex 1. Whereas global production data of minerals and metals is generally provided by geological surveys, such data may be more dispersed for biotic materials. However, several trade databases exist that may provide information at even a more detailed, and downstream, level than for metals, such as Eurostat. In Annex 2, an example of potential data sources suggested by ChatGPT for the supplying countries of wood to Spain is given, showing the potential to identify useful data sources via Artificial Intelligence.

6.2.3 Data quality

Data quality is a notorious limitation for criticality studies, although few criticality assessments transparently communicate about this topic (Schrijvers et al. 2020c). Data quality can be assessed on multiple aspects, such as temporal, technological, and geographical representativeness, reliability, and completeness. For some indicators, uncertainty ranges may be calculated via a Monte Carlo analysis, based on determined uncertainty distributions, e.g. as applied by Graedel et al. (2012). However, several criticality indicators have a semi-

quantitative nature, and value-choices are applied in the scaling and normalisation of the indicator scoring. This makes the determination of uncertainty distributions not senseful, and a different uncertainty rating may be considered. Schrijvers et al. (in preparation) suggest communicating the representativeness of country-specific criticality indicators by indicating the percentage of supply covered by the indicator. For example, if 20% of the supply of a material is provided by “other countries”, which are not characterised, the indicator score country representativeness is valued as 80%. However, a systematic assessment of uncertainty in criticality ratings requires more research which is out of scope of this report. Future research could be based on a Pedigree-matrix like approach where qualitative info on data representativeness is roughly translated into quantitative uncertainty ranges, as also applied in ecoinvent (Weidema et al. 2013; Ciroth et al. 2016).

6.2.4 Indicator scoring using a novel excel tool – application to the illustrative case study

A data collection template is developed in Excel (Table 6) to facilitate the indicator scoring for the selected indicators at different steps in a product’s value chain. The tool is applied to the intermediate flows of the illustrative case study.

Indicator scoring can be applied to different steps in the value chain:

- Availability of reserves (for minerals/metals) or natural growth (of biotic resources)
- Supply from mines (for minerals/metals) or cultivation and harvesting (for biotic resources)
- Production of refined or processed raw materials
- Production of intermediate products
- Production of final products

For each intermediate flow, it is identified at which step in the value chain it is consumed by the “system at risk”, as illustrated in Table 4. This assignment of the value-chain step to an intermediate flow allows to recognize that a supply disruption may take place at the transaction of this intermediate flow, or at any upstream value-chain step.

Table 4. Assignment of value-chain steps to intermediate flows consumed by the system at risk, for the LSL example.

Intermediate flow consumed by the system at risk	Value-chain step
Low-quality green wood	Processed raw material
Electricity	Final product
Virgin sawdust (pine and beech wood)	Processed raw material
Waste biomass (discarded chips, dust, trimmings, and board waste)	Processed raw material
Adhesive material (in this case a polymeric methylene diphenyl diisocyanate glue, in some other cases formaldehyde-based adhesive is used)	Final product

Supply disruptions may be assessed at any point upstream in the value chain. If supply disruptions are assessed at multiple stages (e.g. both the growth of poplar trees and the production of low-quality green wood), the bottleneck is identified. This means that the indicator score of the value-chain step with the highest scoring is maintained for further analysis. If only one value-chain step is assessed, this step is automatically identified as the bottleneck. Therefore, limitations to data accessibility may be managed by modelling only the value-chain step for which data are available, while keeping in mind that supply disruptions at other steps in the value chain may be overlooked.

For indicators that refer to the concentration of supply (i.e. the Herfindahl-Hirschman Index (HHI)), or performance of a supplying country, such as the Worldwide Governance Indicators and the EVI, it is relevant to know from which countries the intermediate flows are supplied. In this example, supply is modelled only for the value-chain step at which the intermediate flow is consumed. This means that, for example, the concentration of the supply of the precursors in the production of the adhesive material is not assessed. Therefore, the implicit assumption is made that the supply bottleneck coincides with the value-chain step at which the intermediate flow is consumed.

For the consumed biotic materials in the illustrative example (low-quality green wood, sawdust and waste biomass) it is assumed that the company sources the raw materials domestically (i.e. from Spain) (see Table 5). Some criticality assessment methods (such as the GeoPolRisk method) consider that domestic supply is risk-free. However, this assumption is not applied in this approach, as domestic supply may be affected by weak regulation or natural disasters. However, some indicators may be less relevant, such as export restrictions. For the adhesive material, the company-specific suppliers are unknown. Based on an overview of global supply of the specific chemical from different continents², simplifying assumptions are made on the supplying countries in these continents, for illustrative purposes only.

Electricity is not prioritized in this illustrative example. Direct electricity consumption has not been considered as a factor of criticality in any study that the authors are familiar with, and is not the priority focus of a criticality assessment of the bioeconomy, especially considering that electricity from different technologies is highly substitutable. However, electricity prices may fluctuate, posing a potential risk on the profitability of an activity. Therefore, it would be interesting to compare the Cumulative Energy Demand (CED) from direct electricity consumption with the CED from other intermediate flows, to identify which flow may be most impacted by increasing electricity prices. Furthermore, a high environmental impact caused by the used electricity mix may result in external pressure (from the government or potential clients) to move towards greener electricity sources. Therefore, the assessment of environmental indicators for electricity use, in comparison to other intermediate flows, may be valuable as well.

Table 5. Identification of supplying countries for the consumed intermediate flows, for illustrative purposes.

Intermediate flow consumed by the system at risk	Supplying countries
Low-quality green wood	Spain (100%)
Electricity	NA
Virgin sawdust (pine and beech wood)	Spain (100%)
Waste biomass (discarded chips, dust, trimmings, and board waste)	Spain (100%)
Adhesive material (in this case a polymeric methylene diphenyl diisocyanate glue, in some other cases formaldehyde-based adhesive is used)	China (50%), Germany (25%), USA (15%), Brazil (7%), Saudi Arabia (3%)

The shares of supplying countries are multiplied with country-specific indicator values in the Excel template, to calculate a weighted average of country-specific indicator scores (Table 6).

² <https://www.polarismarketresearch.com/industry-analysis/diphenylmethane-diisocyanate-mdi-market>

Table 6. Screenshot of the Excel tool that provides an overview of the assessment of country-level indicators for adhesive material. Country scores are weighted-average based on the supply mix to obtain a material-specific indicator score (in column A (the first column of the figure)). Note that country-level data gaps (e.g. child labour for China) result in a lower market representativeness for this specific indicator.

Aggregated scoring of country-level indicators	Total HHI 3408	% of market represented	Production of final product	China	Germany	United States	Brazil	Saudi Arabia
			100% Share					
			0% Export restrictions between 2017-2020	50,0%	25,0%	15,0%	7,0%	3,0%
			WGI - Political stability & absence of					
54,05660412			100% Violence/terrorism (2020)	31,13207626	7,78302	8,06604	4,7547171	2,32075
24,0961541			100% WGI - Government effectiveness (2020)	13,70192337	2,76442	1,94711	4,44230782	1,24038
33,48076851			100% WGI - Regulatory Quality (2020)	25	1,68269	1,875	3,76923073	1,15385
32,28365299			100% WGI - Rule of law (2020)	23,55769157	2,16346	1,73077	3,63461536	1,19712
32,40384586			100% WGI - Control of corruption (2020)	23,55769157	1,20192	2,59615	3,9375	1,11058
58,97584578			100% WGI - Voice and Accountability (2020)	47,58454108	1,44928	4,05797	3,0434782	2,84058
45,46916667			100% Fragile State Index (2022)	29,625	5,14583	4,75	4,18833333	1,76
37,4987			72% Policy Perception Index (2021)	27,775	#VALUE!	6,0585	3,6652	#VALUE!
36,67666667			100% Enabling trade index (2016)	20,91666667	6,29167	4,4	3,73333333	1,335
46,751			100% Environmental Performance Index (2020)	31,35	5,7	4,605	3,416	1,68
0,378			7% Child labour (% ages 5-17) (2010-2019)	#VALUE!	#VALUE!	#VALUE!	0,378	#VALUE!
26,11875			100% Global Peace Index (2022)	14,575	3,0875	4,90125	2,47275	1,08225
43,2			100% Corruption Perceptions Index CPI (2021)	27,5	5	4,95	4,34	1,41
16,468			100% Human Development Index HDI (2019)	11,95	1,325	1,11	1,645	0,438

Indicators that are not country-specific but material-specific may also be assessed at multiple points in the value chain. Also here, the bottleneck value is calculated based on the value-chain step that gives the highest indicator score. This is illustrated in Table 7 for the adhesive material. The orange boxes of Table 7. indicate for which value-chain step data may be inserted. The bottleneck value is then automatically calculated in the final column. The table in Annex 1 indicates for which types of flow (minerals/metals or biotic materials) indicators are relevant to assess. For example, the Policy Perception Index is relevant for metals, but not for biotic materials. This must be considered during the interpretation of the indicator scores.

In Table 7 it is inserted that the adhesive material is considered as a substance of very high concern for authorisation in the REACH framework. Indeed, it is included in the Community Rolling Action Plan (CoRAP) indicating that certain countries will soon assess potential restriction³. Furthermore, some uses of the substance are already restricted. A value of “Yes” automatically assigns the highest indicator score of 100 to this indicator. Also, a datapoint for demand growth has been identified⁴. Based on the available data (e.g. for different time horizons), the bottleneck value for demand increase is calculated.

³ <https://echa.europa.eu/substance-information/-/substanceinfo/100.002.697>

⁴ <https://www.polarismarketresearch.com/industry-analysis/diphenylmethane-diisocyanate-mdi-market>

Table 7. Calculating the bottleneck value based on indicator scoring at multiple steps in the value chain using the Excel tool. Illustration of the assessment of the adhesive material.

	Raw material extracted from nature	Raw material extracted from cultivation (harvesting) / Mining	Processed raw material	Intermediate product	Final product	Bottleneck value
Amount of phosphorous applied (kg) in a product system						0
Amount of land used (h/year) in a product system						0
Cradle-to-gate LCA (single score)						0
Climate change						0
Acidification						0
Eutrophication						0
Ozone Depletion						0
Photochemical ozone formation						0
Cumulative energy demand						0
Threatened Species Index (TSI)						0
Primary material use (%)					100%	100%
Extraction rate						
Resource stocks						
Replenishment rate (biotic resources)						
Biotic resource depletion						#DIV/0!
Growth rate						
Yield						
Replenishment rate (man-made biotic materials)						0
Substance of very high concern for Authorisation (REACH framework)					Yes	100
% supply as by-product						0%
Compound Annual Growth Rate between 2020-2030					5,2%	5,20%
Compound Annual Growth Rate between 2018-2040						0,00%
Compound Annual Growth Rate between 2020-2050						0,00%
Production/consumption increase/decrease over the last five years						0,00%
% expected demand growth						5,20%

6.3 Indicator aggregation and criticality determination

6.3.1 Aggregation method

Many criticality assessment studies have the ambition to calculate a final criticality score, in which scores at an indicator level are aggregated. The aggregation of indicators allows to produce a final ranking of CRMs, or to establish a multi-dimensional criticality matrix if aggregation is only applied to sub-categories (such as supply risk and vulnerability to a supply disruption in the EU methodology). This enables the prioritization of raw materials that have the highest supply risk, and subsequently adopt mitigation measures.

The drawback of the application of an aggregation procedure is that there is no scientifically established aggregation method. Indicators are often aggregated based on a constructed mathematical formula (e.g. in the EU methodology) or by the application of subjective weights (e.g. by Graedel et al. (2012)). Bach et al. (2017) do not recommend a specific aggregation procedure, but they do suggest aggregating the indicators within the individual dimensions of their method (i.e. physical constraints, environmental constraints, social constraints, abiotic constraints, and socio-economic constraints). This already shows a limitation of aggregation, as the indicators of the BIRD method have been restructured to be linked to the three risk types as applied in this report: accessibility problems, price fluctuations, and reputation damage. Some indicators contribute to multiple risk types, and some indicators have complementary or a reinforcing role in the assessment of the risks. This could result in an overestimation of the scoring of certain dimensions. Besides, aggregation results in a lack of

information at an indicator level, which is valuable for the understanding of different supply risk sources and can be the key information obtained from the criticality assessment, as also recognized by Bach et al. (2017).

Due to the limitations of aggregation, it is recommended to present criticality scoring per indicator level. However, in order to interpret the indicator scoring (e.g. to understand if the indicator scoring is “high” or “low”), multiple datapoints are necessary. Multiple datapoints can be obtained by the following types of comparison:

- Comparison of multiple life cycle stages, such as cultivation, production of intermediate materials, and production of final goods.
- Comparison of different raw materials, such as different wood species (see Ioannidou et al. (2019))
- Comparison of different intermediate flows entering the same system
- Comparison of a biotic material with an extensive database of raw materials, which may include also indicator scorings for minerals and metals. For example, the assessment of a specific wood type may be compared with the raw materials available in the IRTC Decision Tool (IRTC 2023), to understand whether bottlenecks are comparable to cobalt, lithium, or copper, for example. The drawback of this comparison is that some indicators are specific to biotic materials, and no extensive database is available yet that includes a wide range of biotic materials.

Assessment of raw material criticality at an indicator level has as disadvantage that the study is less compatible with LC(S)A studies that aim to add “criticality” as an additional impact category, to be evaluated alongside several environmental impact categories. However, the usefulness of such a single criticality impact category is debatable. Key applications of a criticality assessment are to understand potential sources of supply risks and to identify mitigation strategies to mitigate these risks, in order to protect an (economic) entity that is dependent on the availability of a certain raw material. A comparison of the level of criticality of two raw materials or two products in a specific case study already implies their substitutability for the intended audience of the criticality study, making the raw materials inherently less critical in this specific context. Furthermore, the underlying sources of risk of a final criticality rating may require different mitigation strategies, and stakeholders may be more equipped to manage certain types of risks, rather than others. This negates the benefit of comparing the final criticality score of two raw materials and justifies the exclusion of this aggregation step altogether.

6.3.2 Application of a threshold value

The application of a threshold value to distinguish “critical” from “non-critical” raw materials is another topic of debate, especially in the scientific community (Schrijvers et al. 2020c). Bach et al. (2017) apply a “distance-to-target” approach in the BIRD method to determine whether a raw material has a high or low score on a certain indicator, hence whether it is critical or not. The target may be based on stakeholder consultation or expert judgment, or simply by the judgment of the study authors (Bach et al. 2017b).

In the IRTC tool, a flexible threshold value is introduced that allows the user of the tool to select the 25%, 33%, or 50% highest ranking raw materials for a specific indicator. However, the application of such a threshold value requires the availability of a large number of datapoints to compare a specific raw material with.

Criticality is by definition a relative determination, so in many studies it may be sufficient to know that a specific raw material scores “higher” on a certain indicator than another raw material, which allows to identify specific issues in a raw material’s value chain in a comparative study. Therefore, no threshold value is recommended within this project. However, criticality assessments benefit from the scoring of a broad range of raw materials, which put the scoring of a single raw material (or intermediate product) in perspective. As the method presented in this report has not been broadly applied yet, as an intermediate benchmark, a threshold value determined

by the distance-to-target approach, such as applied in BIRD, may be temporarily used, to facilitate the interpretation.

6.4 Interpret and communicate the results

In the illustrative case, the indicator scores of the different intermediate flows are compared among one another, and also compared to the scoring of cobalt and lithium using the IRTC tool (Table 8). Cobalt and lithium are chosen as reference materials, as these are both considered as “critical” and “strategic” by the European Commission (European Parliament and Council of the European Union 2024), although their supply situations are different.

Table 8. Impression of the overview of indicator scoring for the intermediate flows of the illustrative example, as well as for cobalt and lithium.

Indicator	Low-quality green wood	Electricity ⁵	Virgin sawdust	Residual biomass	Adhesive	Cobalt	Lithium	Max
Supply is dominated in a few countries (bottleneck)	100,0	#REF!	100,0	100,0	81,2	88,0	83,7	100,0
WGI - Political stability & absence of Violence/terrorism (2020)	42,0	#REF!	42,0	42,0	54,1	78,3	56,0	78,3
WGI - Government effectiveness (2020)	22,1	#REF!	22,1	22,1	24,1	77,2	26,3	77,2
WGI - Regulatory Quality (2020)	26,4	#REF!	26,4	26,4	33,5	77,7	35,7	77,7
WGI - Rule of law (2020)	21,6	#REF!	21,6	21,6	32,3	80,1	33,1	80,1
WGI - Control of corruption (2020)	23,6	#REF!	23,6	23,6	32,4	79,8	31,7	79,8
WGI - Voice and Accountability (2020)	19,3	#REF!	19,3	19,3	59,0	72,5	50,2	72,5
Fragile State Index (2022)	33,9	#REF!	33,9	33,9	45,5	76,2	43,5	76,2
Policy Perception Index (2021)	41,1	#REF!	41,1	41,1	37,5	48,4	34,8	48,4
Enabling trade index (2016)	28,7	#REF!	28,7	28,7	36,7	54,6	36,5	54,6
Environmental Performance Index (2024)	36,0	#REF!	36,0	36,0	50,1	56,2	51,5	56,2
Child labour (% ages 5-17) (2010-2019)	0,0	#REF!	0,0	0,0	0,4	10,9	2,7	10,9
Global Peace Index (2022)	17,8	#REF!	17,8	17,8	26,1	45,8	25,0	45,8
Corruption Perceptions Index CPI (2021)	39,0	#REF!	39,0	39,0	43,2	69,6	44,9	69,6
Human Development Index HDI (2019)	9,6	#REF!	9,6	9,6	16,5	41,7	18,1	41,7
Natural disaster Index (NDI) (2013)	3,1	#REF!	3,1	3,1	18,4			18,4
Economic Vulnerability Index (2024)	0,0	#REF!	0,0	0,0	12,3			12,3
Economic Vulnerability Index - Share of agriculture, forestry and fisheries (2024)	0,0	#REF!	0,0	0,0	4,5			4,5
Economic Vulnerability Index - Remoteness and landlockedness (2024)	0,0	#REF!	0,0	0,0	22,1			22,1
Economic Vulnerability Index - Export concentration (2024)	0,0	#REF!	0,0	0,0	2,2			2,2
Economic Vulnerability Index - Export instability (2024)	0,0	#REF!	0,0	0,0	1,2			1,2
...	...	...	...	...	...	...	...	...

As not all indicators are assessed on a scale of 0 – 100, scores are normalized to the flow with the highest score. Scores can then be plotted in a graph (Figure 10), allowing for the identification of criticality hotspots.

⁵ Electricity is not currently evaluated within the tool, resulting in the generation of an error value (#REF!)

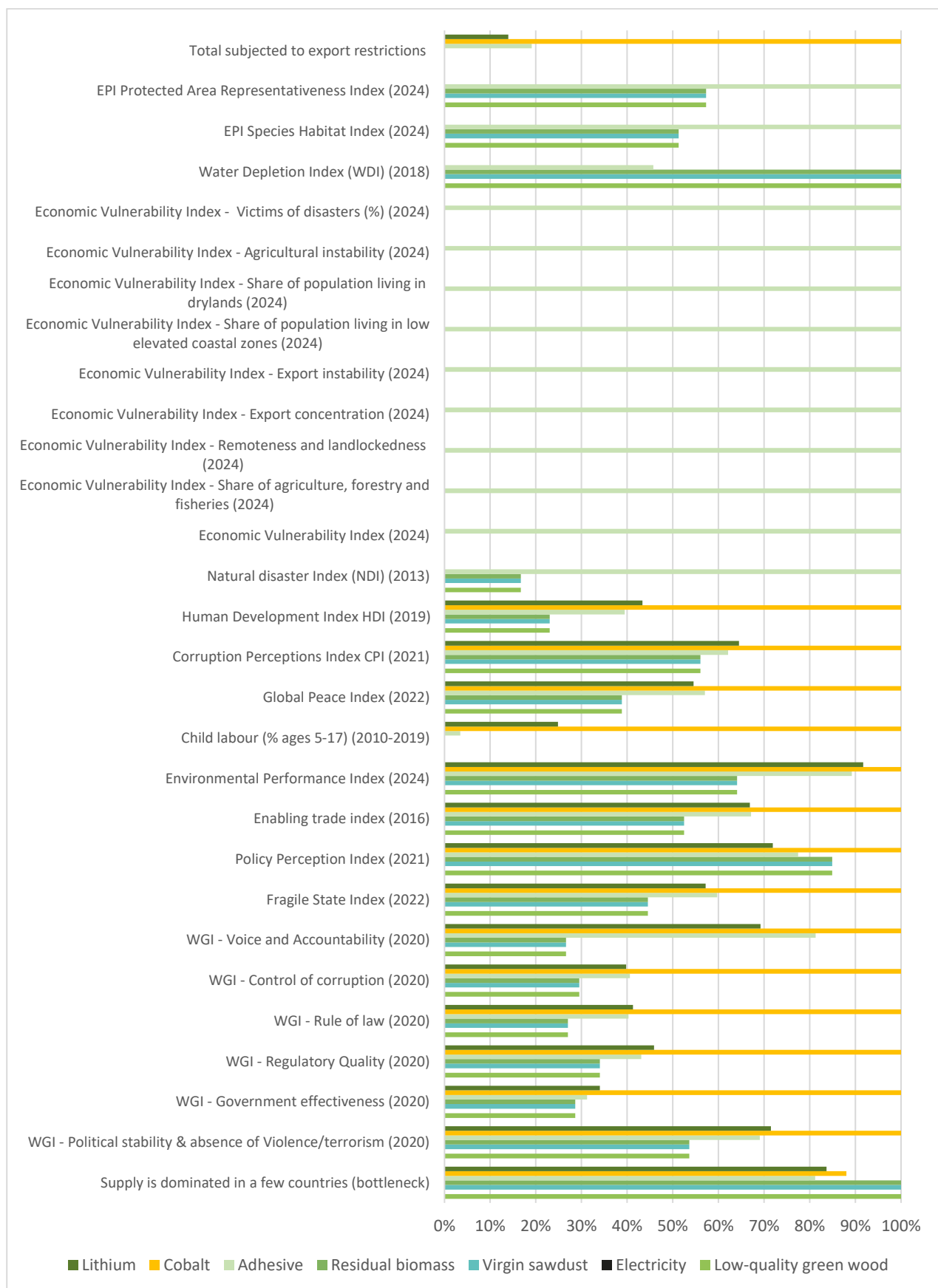


Figure 10. Comparative assessment of criticality indicators of the intermediate flows of the producer of LSL, and cobalt and lithium.

From Figure 10, the following observations can be made. The supply of the biotic materials to the producer of LSL (the green wood, sawdust, and residual biomass) is strongly concentrated, as it was assumed that these materials are all domestically sourced. A highly concentrated supply may result in difficulties accessing the product or raw material, as well as potential shortages in the (local) market. In this assessment, only the current suppliers of the company are evaluated. It is interesting for the LSL producer to identify other potential suppliers, both within Spain and outside Spain that may be able to provide the required raw materials to produce LSL.

For many other indicators depicted in Figure 10, the intermediate flows of the LSL system can be considered less critical than cobalt. Cobalt is highly critical due to the strong concentration of supply from the Democratic Republic of Congo, and the relatively weak scoring of this country on country-specific indicators such as the Worldwide Governance Indicators and trade policies. Intermediate flows of the LSL system have a scoring more comparable with lithium, as lithium is mostly supplied by Australia and Chile, which are considered as more politically stable countries. The adhesive material has a higher supply risk than the biotic materials, due to the reliance of supply from (mostly) China rather than Spain.

The Economic Vulnerability Indices have not been quantified for Lithium and Cobalt. Due to data gaps for Spain for these indicators, only the adhesive material is scored. As it is the only score, it is automatically considered the highest. As there is no reference point for these indicators, it cannot be stated whether the adhesives has a high or low score on these indicators.

Regarding the sub-indicators of EPI (Environmental Performance Index), Spain performs better than the average supplying country of the adhesive materials. However, Spain is known for a relatively high water scarcity, giving the biotic materials supplied by Spain a relatively high score.

Whereas Figure 10 shows a selection of country-specific indicators, Figure 11 focuses more on material-specific indicators. Here, it is evident that many of the indicators are not quantified yet. For a few indicators, a score is available for cobalt and lithium, as those indicators have been quantified in the context of the IRTC tool. The indicators that are newly added to the IRTC framework, as provided by BIRD, are not quantified for any material yet. Whereas some of the indicator scoring can be based on LCA studies, others may require an additional literature review, such as the assessment of the replenishment rate of biotic materials.

A few indicators are relatively easy to quantify. For example, the flows low-quality green wood, sawdust, and residual biomass are easily identified as by-products, therefore, they are scored as 100% supplied as by-products. This by-product dependency is a risk factor, as, if the demand for the main product (e.g. high-quality green wood) declines, the by-product (low-quality green wood) becomes inaccessible as well. This could lead to market shortages and strong price fluctuations (see Figure 9). Furthermore, as mentioned above, the adhesive material presents a high risk regarding its potential toxicity. If certain countries restrict its use in certain applications, the producer of LSL may need to find a substitute material, potentially at a higher cost. Furthermore, there is a risk that consumers are reluctant to use the LSL panels containing this specific type of adhesive.

The indicators “potential to recycle” and “primary material use” have not been assessed in the IRTC tool. Here, the potential to recycle is scored highly if the potential is low, indicating a higher risk. The sawdust, residual biomass and adhesive are considered difficult to recycle, due to their (assumed) dissipative use in the market.

According to the cause-and-effect diagram of Figure 9, this means that it may be difficult to upscale supply with an increased demand. However, this risk may be more relevant for products that are also a by-product (such as sawdust and residual biomass) than for the adhesive material, for which additional primary production capacity may be installed.

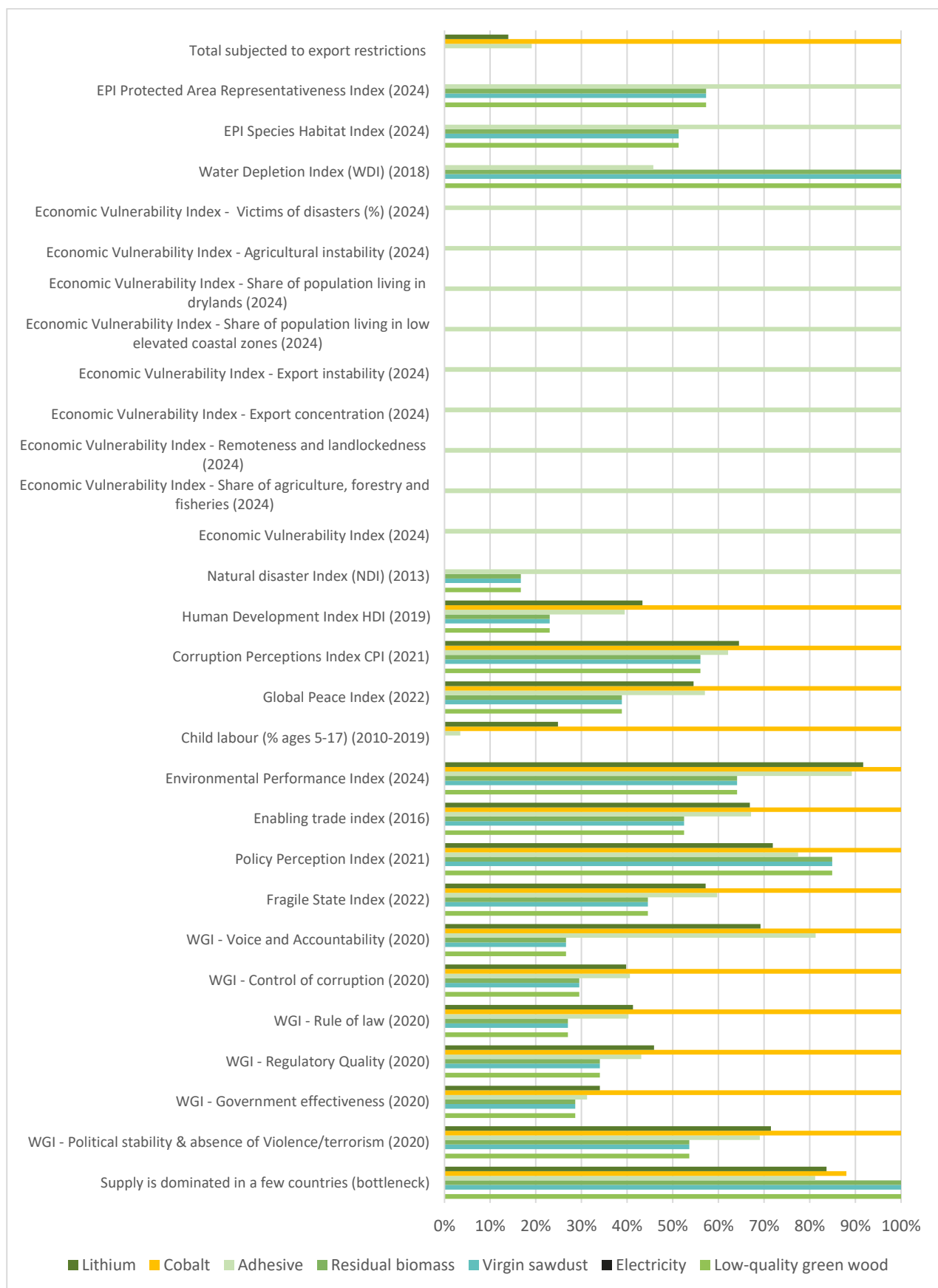


Figure 11. Comparative assessment of criticality indicators of the intermediate flows of the producer of LSL, and cobalt and lithium (continuation).

In this illustrative case, the quantification of indicators has been limited to basic assumptions. If indicators cannot be quantified in a criticality assessment, the indicators may be excluded from the analysis. However, such indicator exclusion (and the corresponding risk types) is a limitation of the study and must be communicated as such. However, this illustrative case shows that the assessment of intermediate flows based on a few data points (including the supplying countries) already provides information that indicates a few relevant criticality hotspots, especially if more contextual data are available (i.e. example scoring from the IRTC tool, or comparative scoring from a single case study).

Depending on the formulation of the “system at risk”, the communication of the criticality hotspots should be adapted to audiences with a specific interest to these results. If the system at risk is a producing company, such as in the illustrative example, communication should be focused on internal stakeholders, such as purchasing or R&D departments, that must become aware of potential risks related to current practices and need to be motivated to adapt these practices. Also, potential investors in the company may be interested in these results, as they may ask for (additional) efforts in securing the company’s operations. However, the results are less suitable for the general audience, unlike the results of a (positive) LCA study, as the general audience may be less concerned with the future stability of a specific company. If the system at risk is formulated at a different scale, such as a national or the European economy, it becomes more relevant to expand the targeted audience, as policy decisions (such as stimulate mining within Europe) based on the identified criticality hotspots must be justified. Furthermore, a broader audience becomes affected by the “local prosperity” generated by the system at risk, due to their interest in a stable access to employment and goods.

7 CRITICALITY MITIGATION

7.1 Mitigation for biotic materials

Once criticality hotspots are identified, potential measures may be considered to mitigate the identified supply risks. Schrijvers et al. (in preparation) collected a broad range of mitigation measures relevant to mitigate risks related to the supply of metals and minerals. These mitigation measures may either decrease the probability that a disruption in the supply takes place, or they mitigate the potential damage caused by a disruption on a company (Figure 12). These mitigation measures are integrated into the IRTC tool (IRTC 2023) and a detailed description of each mitigation measure is provided, including potential implementation hurdles and needs for collaboration with other stakeholders.

Figure 12 has been updated to Figure 13 to include mitigation measures for biotic materials. Mitigation measures added (compared to the mitigation measures included in the IRTC tool) are:

- Optimize storage logistics, for example by technological innovation (managing atmospheric gasses).
- Starting new production sites, such as new plantation sites. Note that this may have a detrimental effect on current levels of biodiversity, such as the replacement of tropical forests by soybean or palm oil plantations in Brazil and Indonesia.
- Increase production efficiency, in order to increase the biomaterial output per unit of land or water consumption. Note that this measure may lead to increased monocultures, reducing local biodiversity and increasing the risks of pests.
- Open new processing facilities.

Mitigation measures must be evaluated regarding the potential trade-offs between the economic stakeholder’s stability, environmental damage, and social needs. Furthermore, some mitigation measures may require investments in technological development, such as the identification of substitutes.

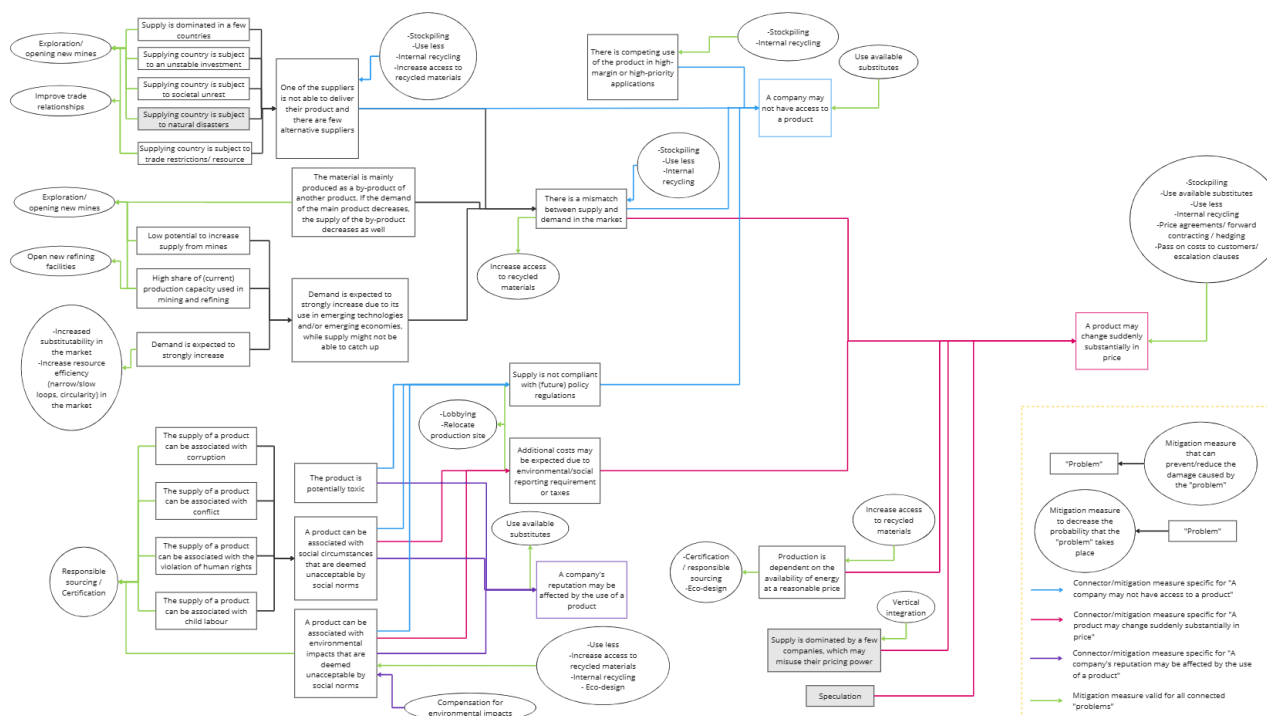


Figure 12. Mitigation measures relevant to different types of risks, that either can prevent a supply disruption from taking place, or prevent a company from experiencing damage from such a disruption (Schrijvers et al., paper in preparation).

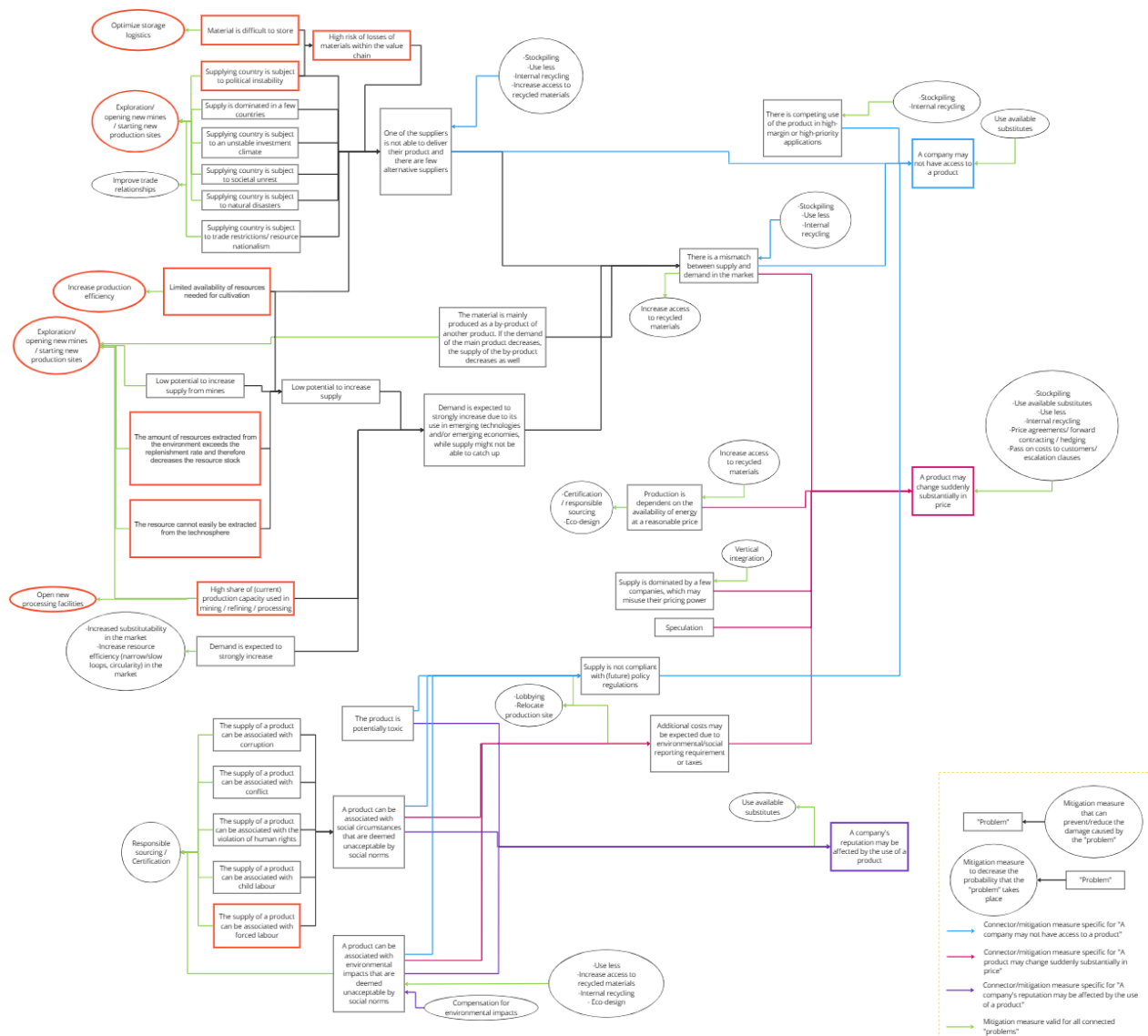


Figure 13. Mitigation measures relevant to different types of risks, that either can prevent a supply disruption from taking place, or prevent a company from experiencing damage from such a disruption, updated to include mitigation of risks specific to biotic material (Schrijvers et al., paper in preparation).

7.2 Potential of circularity strategies to increase supply security

As can be observed in Figure 13, several mitigation measures refer to circularity strategies (as further reviewed by Tercero Espinoza et al. (2020):

- **Internal recycling:** this measure may result in an overall decreased demand for raw materials by the system at risk. Increased resource efficiency may lead to reduced costs (especially if raw material prices increase) and the potential to continue producing a certain amount of goods, when raw materials become more difficult to access. A decreased input of raw materials in the system at risk furthermore generally results in decreased environmental impacts attributed to this system, depending on the applied allocation method in a corresponding LCA study (see the Circularity chapter of this report).
- **Increase access to recycled materials:** The potential to use recycled materials, next to primary materials, results in an increased diversified supply. Recycled materials may be supplied by countries that do not have the potential to produce primary materials. Recycled materials often also have a lower

environmental footprint, although this must be verified by an LCA study. However, it must be highlighted that recycled materials are by definition a by-product. If the product that provides the recycled material at the EoL changes its material composition, or demand for this product is decreased, access to recycled materials may become limited as well.

- **Increase circularity in the market:** Whereas the above circularity strategies refer to the direct consumption of recycled materials by the system at risk, circularity implemented by other systems may be beneficial as well. If the demand for certain raw materials is expected to strongly increase, improved circularity in systems in which this is easily implementable can result in limited demand growth, and a decreased pressure on the overall market. This may result in improved access and limited price constraints in the overall market.

Yet, it may be that circular economy practices, may have other criticality risks in their material use and or supply chain, e.g. by the introduction of new processes (e.g. new recycling processes, extra transportation) and alteration of processes which in their turn may harbour other criticality issues (Schaubroeck 2020). This urges to still do again a criticality assessment of the circular alternative and not take its supply for granted. It must be noted that the increased EoL recycling rate, or increased recovery at the EoL, is considered of limited effectiveness in increasing supply security. As long as recycled materials may not be used in a closed loop, the stakeholder that relies on the use of primary materials may not be able to decrease its dependency on raw materials. Only with regard to environmental impacts, an increased recovery at the EoL may result in a lower association with environmental impacts. In Figure 13, an improved EoL recycling rate may then be considered as an “eco-design strategy”.

7.3 Application of mitigation measures to the illustrative case study

Based on the hotspot analysis of the illustrative case study (i.e. production of LSL), the following mitigation measures may be identified:

- **Identify new suppliers:** The fact that the supply of biotic materials (low-quality wood, sawdust, and residual biomass) is strongly concentrated in Spain, and potentially concentrated by a single supplier, can be mitigated by identifying other potential suppliers of these materials. It may already be helpful to identify other suppliers within Spain, but ideally the supplying region is diversified, to limit the risk that all suppliers are affected by a natural disaster such as wildfires. Ideally, suppliers from other European countries are identified as well, as European countries are generally reliable trade partners.
- **Stockpiling:** Stockpiling of the intermediate flows may help to overcome short supply restrictions. However, stockpiling of biotic materials may be challenging, due to the possibility that the stock is sensitive to moisture and other atmospheric conditions.
- **Increase access to recycled materials:** Although the biomass used to produce steam is not recyclable, there may be possibilities to create access to the LSL panels that reach their EoL. This can be enabled by the establishment of long-term customer relationships or the implementation of a take-back system. However, the costs of implementing such a system and the potential limited quality of the EoL LSL panels may be limiting factors in the implementation of this measure.
- **Use less:** In periods of scarce access to the biotic materials, it may be useful to be able to produce products that have a lower material intensity, while maintaining the initial functionality. This may be achieved by using different production techniques or more efficient adhesives, for example. Regarding the use of biotic materials for the on-site production of steam, investing in a more efficient steam generator, or decrease the overall demand for steam, may be possibilities to limit the consumption of raw materials.

- **Use substitutes:** The ability to use substitutes is invaluable for all potential supply disruptions. The fact that certain raw materials are by-products may lead to disrupted accessibility or strong price fluctuations. In that case, the option to use a different raw material (maybe even high-quality green wood) or a different type of residual wood, even for a short time, could be useful. Furthermore, the fact that the used adhesive material may be potentially toxic should motivate the identification of potential substitutes as well, as in the future, the use of this material may be restricted.
- **Lobbying:** The implementation of restrictions for the use of a potentially toxic adhesive may be delayed or avoided by lobbying efforts, together with other industrial users of the adhesive. However, trade-offs between ongoing business operations and social needs of consumers must be taken into consideration, especially from a sustainability point of view.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Criticality awareness

This report provides a new perspective on the evaluation of raw material criticality of biobased products, considering potential supply disruptions of raw materials and intermediate goods, which can be both from biotic as abiotic nature. For such an assessment, relevant indicators for different types of raw materials are combined in a single assessment framework, which focuses on a set of risk types, rather than on different indicator dimensions.

While other methods have focussed on comprehensiveness of sustainability assessment and/or the provision of a single result, we argue for a step-wise procedure that explicitly identifies an economic stakeholder of interest, allowing for the identification of sources of potential economic instability and mitigation measures. A criticality assessment following this approach is less quantified than an approach based on characterisation factors that calculates a final single score. However, it emphasizes the interplay between different sources of supply disruptions, different potential effects this may have on a specific company or a defined regional economy, mitigation measures, and applies a defined stakeholder perspective, allowing for the provision of information that is easily interpreted and can inform concrete actions.

To ensure that a criticality assessment provides valuable information to the relevant economic stakeholders, we suggest that the following procedure be followed:

1. Define the economic stakeholder(s) of interest during the goal and scope of the study (e.g. one or multiple companies, a regional economy, or the global economy).
2. Identify which activities in the value chain generate (most) added value to the economic stakeholder under study.
3. On what elementary and intermediate flows do these activities rely?
4. Identify the relative likelihood of a supply disruption (“red flags”) at the level of raw materials, but also at the level of components, semi-finished products, and final goods, depending on the availability of data.
5. What would be the damage to the defined stakeholder if supply is disturbed? Will it lead to increased costs, or potentially a decreased demand by consumers? Example questions to be answered are “How much added value is at stake?”, and for national-level assessments “Which policy goals (e.g. climate neutrality or provision of jobs) may be at stake if goods cannot be delivered?”
6. Formulate a mitigation implementation strategy to prevent that a disruption takes place or to prevent that it causes any damage to the stakeholder under study.

The application of the criticality framework to an illustrative case in the bioeconomy demonstrates the steps to be followed in such a criticality assessment, the kind of information obtained, and the type of conclusions that can be taken.

The current criticality assessment framework can therefore be applied as:

- an initial checklist of value-chain attributes that may affect the stability of the “system at risk”,
- a contextualization of indicator scoring, in which different material flows can be compared among each other, and
- an interpretation tool to understand the relevance of indicators.

8.2 Criticality mitigation

One of the objectives of conducting a criticality assessment may be the identification of potential relevant mitigation strategies. The framework presented in this report suggests mitigation strategies, both for minerals/metals and biotic materials, based on the identified supply risk hotspots.

Mitigation measures must be assessed based on their effectiveness to specific supply risks (e.g. accessibility problems, price fluctuations, or reputation damage), and on their potential effect on avoiding a specific disruption, or mitigate the damage caused by a disruption. This report, combined with the IRTC Decision Tool (IRTC 2023) provides furthermore practical reflections in the implementation of mitigation measures, such as potential trade-offs and implementation hurdles.

8.3 Data needs

Criticality assessment rely on available data from different domains, such as quantitative flows, trade data, market outlooks, and environmental exchanges. Whereas data sources for criticality assessments of minerals and metals are relatively known, indicators for biobased materials are less mature and data sources are less centralized. In this report, we provide a starting point with suggested data sources to assess the criticality of biotic materials, based on recommendations provided by literature. Furthermore, we recommend the use of Artificial Intelligence to explore new data sources that are relevant for the trade of biotic materials.

It is demonstrated that criticality awareness can already be increased among economic stakeholders by a limited access to indicator data. A pragmatic approach in assessing criticality is focussing on the value-chain step for which data are available, and for assigning indicator scoring based on one’s current knowledge on the value chain. The criticality framework, combined with indicator scoring of other flows, provides an increased understanding in the relative importance of a specific indicator, even if data quality is low.

The adaptation of the Goal and Scope of a criticality assessment with a focus on the identification of hotspots and the subsequent identification of mitigation strategies, rather than the quantitative assessment of criticality in a final criticality score gives more room for the use of proxy data or qualitative estimations.

8.4 Future research

One of the limitations that was identified in Deliverable 1.3, and which has only been shortly mentioned in this deliverable, is the role of criticality in a LCSA. It was already mentioned that criticality may fit to assess the economic sustainability of a system. However, the accessibility of environmentally friendly goods for a defined community also addresses environmental and social aspects, respectively. Future research may further explore this role, considering diverging interpretations of what an LCSA should address.

9 PART II – CIRCULARITY

10 INTRODUCTION

10.1 Overview of relevant circularity strategies

A comprehensive literature review was carried out to identify circularity strategies pertinent to the five bio-based sectors addressed by the CALIMERO project: pulp and paper, construction, biochemicals, woodworking, and textiles. The review primarily utilized peer-review articles found in Google Scholar to explore circularity strategies applicable across these sectors, though their relevance varies in significance depending on the specific sector, as detailed in Table 9. Descriptions and definitions of these strategies, shown in Figure 14, were drawn from ISO 59004:2024 standards where applicable. Additionally, sector-specific strategies pertinent to bio-based materials and systems, such as Sustainable Forest Management and mulching, were included, referencing sources such as Brás et al. (2024) and Lier et al. (2022). This systematic approach ensured the inclusion of both generalized and specialized strategies tailored to the unique characteristics of bio-based sectors.

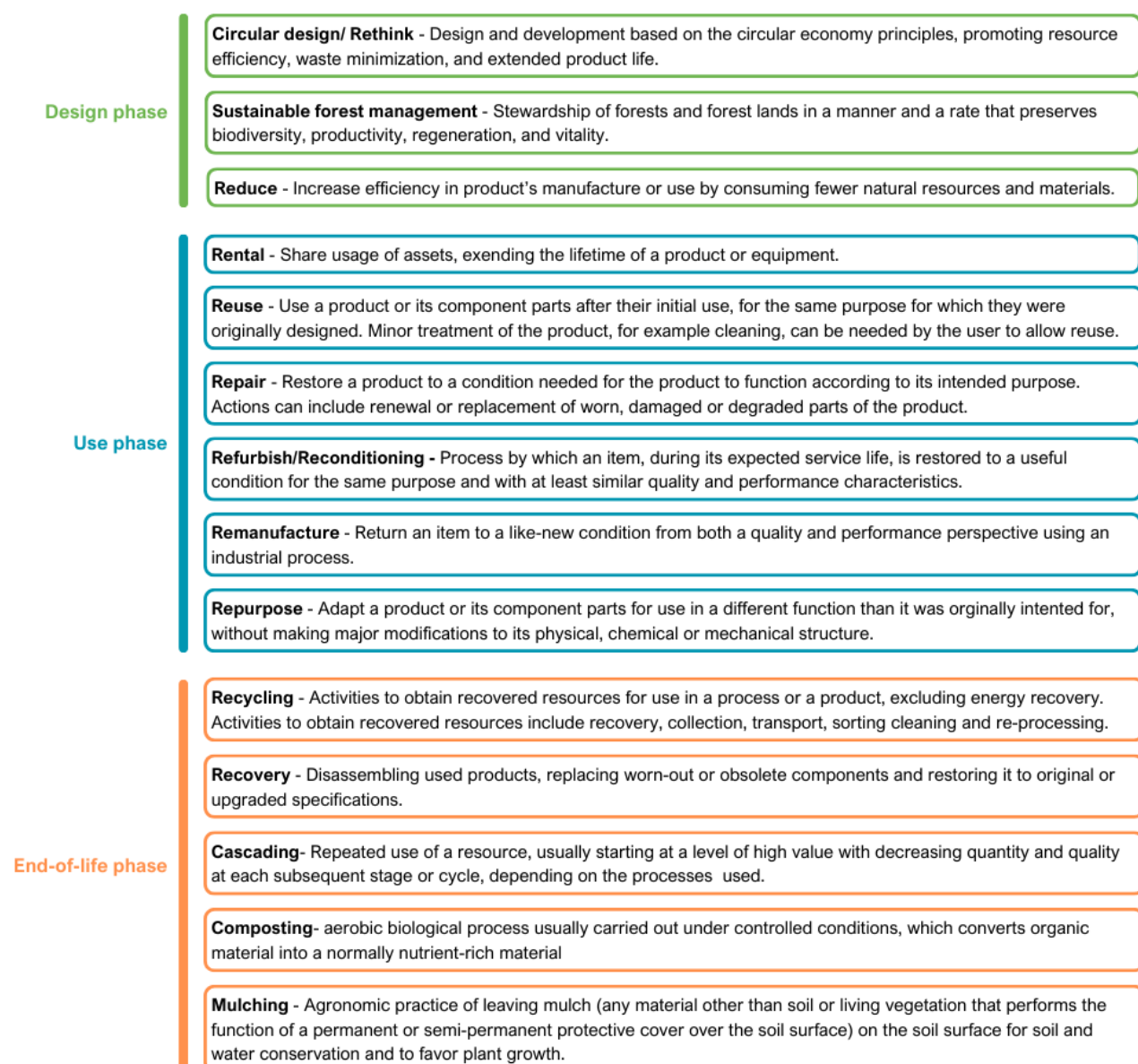


Figure 14. Definitions of circularity strategies as used in this report (ISO 59004:2024).

10.2 Gaps to assess the sustainability performance of the circularity of biobased products

10.2.1 Overview of gaps

In Deliverable 1.3, the following conceptual, modelling, and data gaps were identified that limit a complete quantification of the effects of circularity in (environmental) LCA.

Table 9. Overview of conceptual, modelling, and data gaps for the assessment of circularity of bio-based products in LCA.

Type of gap	Description	Relevance for bio-based sectors
Conceptual	The role of specific circularity indicators in parallel to LCSA as decision support towards a systemic optimisation of bio-economic cycles answering a range of competing needs	All
Modelling	CFF: sector-specific guidance in modelling the CFF may be needed	All
	CFF: inconsistencies regarding the combination of attributional and consequential principles have been identified	All
	Assessing the quality of bio-based materials across finite (e.g. 5 times instead of infinite recycling) and variable loops (e.g. altering recycling efficiency) over time	- Reuse in limited number of loops - Recycling in limited number of loops - Cascading use
	How can multifunctionality for different circularity strategies be modelled in LCA - How to define functional unit - How to put system boundaries - Which allocation strategy to apply - Applicability of CFF	All
	Time-differentiated impacts (dynamic carbon footprinting)	
	Addressing the longevity of products	All
	Allocation of biogenic carbon (credits) and carbon storing capability to successive product systems	All
	Modelling of complex cascading chains of biomaterials in comparison to other materials (minerals, metals, and plastics). For instance, timber products used in construction can cascade into paper products.	
	Modelling of effects of CE in S-LCA and LCC	All
Data	Availability of LCI data of end-of-life activities of bio-based life cycles as well as product functionality and substitution rates.	All

10.2.2 Modelling multifunctionality in LCA

A core challenge when evaluating circular systems in the field of LCA is how to distribute environmental impacts related to the recycling and recovery of materials among the different product systems and life cycle in which the materials are used. This is called the multifunctionality problem (Guinée et al. 2004; Heijungs and Guinée 2007).

Processes are multifunctional when they have multiple functional flows, such as the production of two products (co-production), the treatment of two waste streams, or the combined function of waste treatment and the production of one or more products (recycling or waste recovery) (Guinée et al. 2004). In the context of circular economy, the latter is of main concern; the waste treatment process is shared by the supplier of the waste and the user of the product (Schaubroeck et al. 2021a). In CE, this can be over multiple loops and differences in quality preservation, i.e. the cascading use of a material providing different functionalities. For example, in a wood cascading system, there might be structural wood (first product), which is then converted into chip boards (secondary product) and incinerated with energy production (third product).

10.3 Aim of the circularity section

This report aims to provide recommendations on how to assess the sustainability of circularity strategies in bio-based sectors. A focus is put on the environmental assessment via Life Cycle Assessment, although social LCA and Life Cycle Costing are addressed as well. Within environmental LCA, prominent assessment methodologies are evaluated, and guidance is formulated on modelling of multifunctionality. For each of these methods, clarity is provided on how other circularity modelling gaps are addressed. Finally, the complementarity of different LCA modelling methods and stand-alone circularity indicators is discussed.

11 METHODOLOGY

In the following sections, different approaches to model circularity situations in LCA are introduced. In order to highlight the differences between the methods, these are applied to an illustrative case study of insulation based on natural fibres (explained in the next subsection). After this, key aspects and challenges of LCA with a focus on circularity have been highlighted. Finally, certain LCA strategies or types according to their aspects and whether they meet these challenges are evaluated.

11.1 Natural fibre insulation as illustrative case study

In this illustrative case of cellulose insulation, it is assumed that the cellulose is extracted from end-of-life newspapers. Furthermore, the following end-of-life scenarios could be envisaged:

- Landfilling as non-hazardous materials.
- Incineration with energy recovery.
- Fibers are recycled to produce Solid Recovered Fuels (SRF).
- Recovered fibres are used as stabilizing agents in asphalt.
- Boron-impregnated fibres are pyrolyzed to produce biochar, for the production of plant fertilizer (boron as nutrient).
- Recovered fibres 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 Figure 15. .

Table 10 shows the extent to which modelling challenges as introduced in the previous section are relevant to the specific scenarios in the illustrative example, as well as in general.



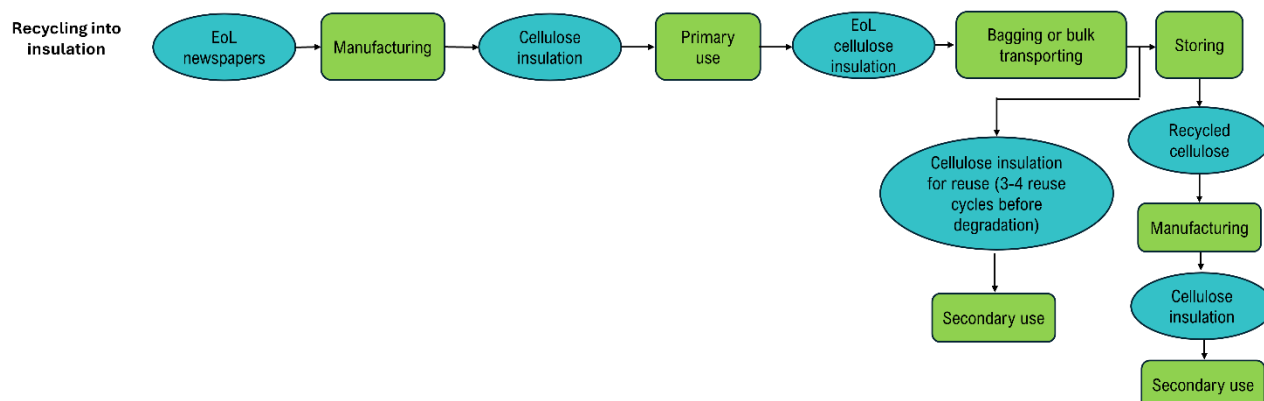


Figure 15. Overview of process flow charts of the different end-of-life scenarios of cellulose insulation.

Table 10. Relevance of circularity modelling challenges to the illustrative case study, and to circularity situations in general.

Challenges	Relevance in illustrative case study of natural fibres in insulation	General reasons for considering this challenge
Time-differentiated impacts (dynamic carbon footprinting)	- Landfilling, due to the long lifetime and gradual emissions of landfills - Recycling into stabilizing agents in asphalt, due to the long lifetime of asphalt - Pyrolyzation to produce plant fertilizer, due to the gradual release of nutrients and emissions by biochar - Reuse/recycling into insulation material, due to the limited number of loops and the delayed final discarding	Circularity strategies have a dire implication on the profile of stressors over time. For example, by reusing or recycling a good before incinerating it, the actual CO ₂ emission of that incineration is postponed.
Addressing the longevity of products	All scenarios	How long or many times a product is used is implicit for many circularity strategies, necessitating the importance of covering this challenge.
Allocation of biogenic carbon (credits) and carbon storing capability to successive product systems	All scenarios	Given again the potential for circular strategies to postpone or limit GHG emissions, the handling of amounts across loops is of concern.
Multiple loops, finite loops, steady/non-steady state	Reuse/recycling into insulation material	The number of loops may differ between circularity strategies, and this should ideally be reflected in the impact score

Cascading chains	Reuse/recycling into insulation material, due potential valorisation after the final insulation loop	Whereas the closed-loop recycling of a material does not pose many challenges in LCA, open-loop recycling, in which a material is used in a different application is often less valued in LCA. However, open-loop recycling may be equally environmentally beneficial, as long as primary raw materials are avoided (Geyer et al. 2016)
Relevance of circularity indicators	All scenarios	The complementary use of Circularity Indicators with LCA has been recommended by the ORIENTING project, although there is seemingly an overlap between the two approaches to access circularity

11.2 Modelling of multifunctionality in LCA

11.2.1 State of the art: Goal-and-scope dependency of modelling of multifunctionality in LCA

There are four key approaches to model multifunctional processes in LCA, focusing on multifunctional waste valorisation and production processes (Figure 16) (Ekvall and Weidema 2004; Schrijvers et al. 2016a; Schaubroeck et al. 2021a).

- **Partitioning** (sometimes referred to as allocation): this approach covers the partitioning of the process/system, its inventories and impacts among the coproducts/cofunctions based on a certain partitioning key. Commonly this is based on a certain property of the coproducts, e.g. their mass or economic value. This approach implies an “accounting” perspective, and the relevance depends on the acceptability of the partitioning criterion (Schrijvers et al. 2021a; Schaubroeck et al. 2021b). Note that the use phase is commonly excluded from this partitioning.
- **Substitution** (avoided burden): In this approach, the inventory and impacts of the total process/system are associated with the product of interest. For additional functional flows (that are not included in the functional unit), it is considered that they can substitute other flows and processes in the market. More precisely, the substitution (avoided burden) effect covers the subtraction of the alternative conventional production of displaced products and processes. This substitution effect is commonly referred to as the “benefits” of waste valorisation.
- **System expansion** (or functional unit expansion (Schaubroeck et al. 2022)): The consideration of all functional flows in the assessment of a product system or process. As the focus of the study is shifted from a single product to all functions provided by a process (or process chain), the study becomes process-oriented rather than product-oriented (Schrijvers et al. 2020).

Cutoff: The cut-off approach attributes certain (parts of) processes to the producer of the waste, and others to the consumer of the valorised product. In practice, this results in a “burden-free” consumption of the valorised product in the subsequent life cycle. The cut-off approach is widely applied in LCA case studies and recommended by many guidance documents (Schrijvers et al. 2016b). However, as, in this approach, waste flows (flows that are not a product nor elementary flow) may exit a product system, this approach is difficult to justify from the perspective of ISO 14044 (Schrijvers et al. 2020). However, following the cut-off criteria of ISO 14044, the cut-off method may be the result of the application of partitioning or substitution, in which the modelled effects are negligible (e.g. for flows with a very low economic value in economic partitioning, or for the substitution of processes with a very low impact) (Schrijvers et al. 2020).

According to the allocation hierarchy of ISO 14044, wherever possible, allocation should be avoided by expanding the product system to include the additional functions related to the co-products (ISO 2006). Within the LCA community, the application of “system expansion” has been interpreted in two distinct manners:

1. “Functional unit expansion” to add the additional functionalities provided by co-products (see e.g. (Heijungs 2014; Schrijvers et al. 2020; Schaubroeck et al. 2022))
2. The application of substitution

This latter interpretation is widespread in the LCA community, and is also referred to in the recent Annex D that has been published as an amendment to ISO 14044 (ISO 2020). According to LCA practitioners applying this second perspective, this latter perspective is “mathematically equivalent” to the first one, which justifies its application (see e.g. (European Commission 2010)). However, as also argued by (Schrijvers et al. 2020) studies that apply the first or the second perspective apply distinct goals and scopes, and the results should be communicated differently. Considering them “equivalent” may result in a misinterpretation of the results by the LCA audience, and an erroneous use of results in subsequent studies. To avoid such misinterpretations, to

illustrate the distinction between applying substitution and system expansion, and to highlight the complementary nature of these two approaches, in this report, **the term “system expansion” strictly refers to the first perspective as listed above, and “substitution” is only used on the context of the second perspective.**

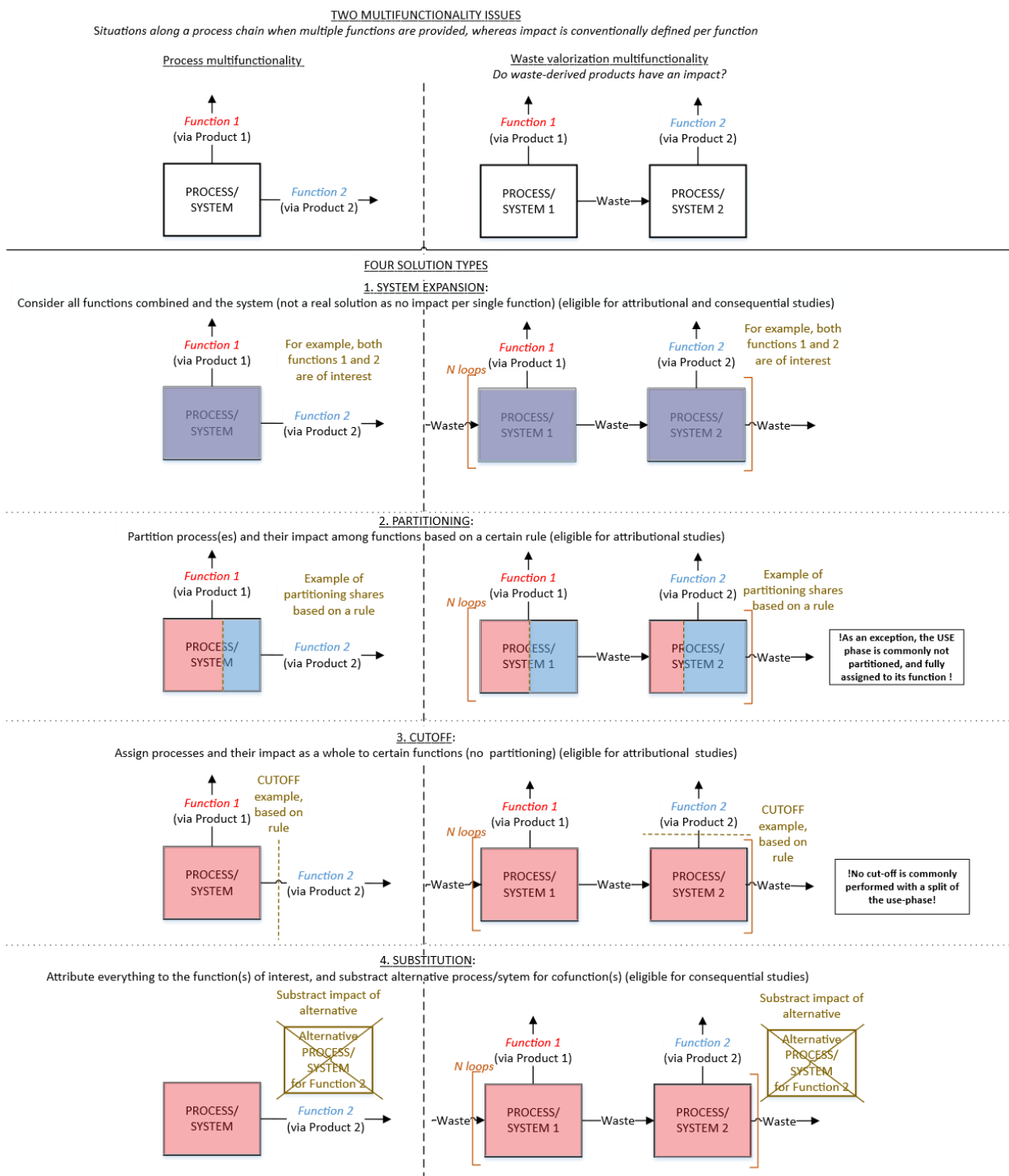


Figure 16. Two types of multifunctionality issues and four modelling solutions. Other combined or derived solutions exist, but here we present these archetypes. Adapted from the work of Schaubroeck et al (2021a). See also references in that work.

11.2.2 Selection of multifunctionality approach based on goal and scope

How to deal with multifunctionality in LCA, like any other methodological choice, should primarily align with the goal of the study.⁶ An LCA study should normally begin with a specification of goal & scope, which then delimits methodological choices and challenges. Different goal aspects should be specified. According to ISO 14044, the goal will 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”.

(Schrijvers et al. 2020) identified different “archetypes” of goal and scope definitions, all asking for a different allocation procedure (Figure 17). The archetypes of goal and scope definitions differ in the application of a process-oriented or product-oriented approach (linked to the reason for carrying out the study), and an attributional or consequential LCA (linked to the perspective of the LCA practitioner and the intended audience).

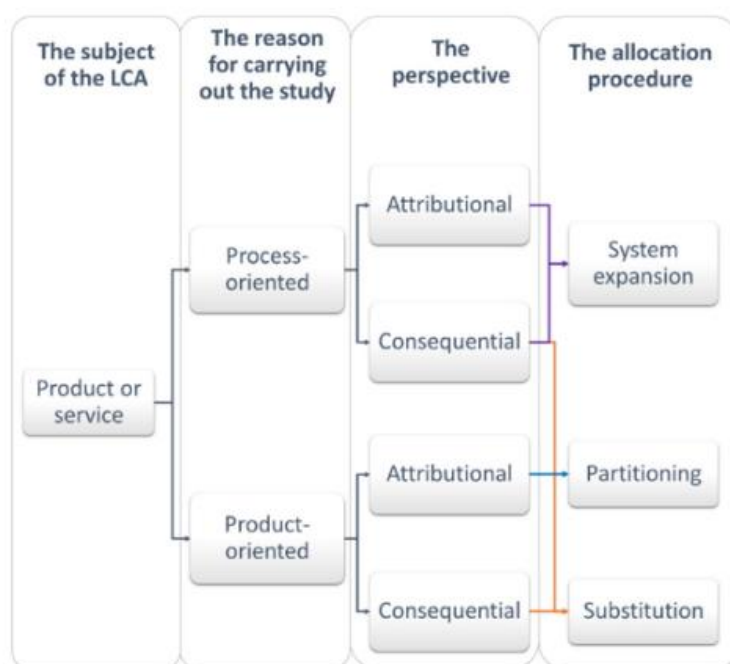


Figure 17. Dependency of the allocation procedure on the goal and scope of the LCA (Schrijvers et al. 2020).

11.2.2.1 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 therefore) or processes/systems as the object of study:

- **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. For a focus on products (or the demands therefore), there is a clear need to somehow solve the multifunctionality issues, in particular with waste valorisation in the context of CE.
- **Process-oriented LCA:** In several contexts the LCA study is focused on the performance of a process.

⁶ 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.

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 of less interest to understand how the impacts of the process are distributed among different product systems. For a focus on process/system, one can apply system expansion, more specifically functional unit expansion, where all products that are created by the process/system are considered all together.

11.2.2.2 *Attributional and consequential LCA*

The perspective of the LCA refers to the scope of impacts that are of interest for the LCA practitioner or the intended audience. Two main 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 analysed 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”. This is according to the UNEP-SETAC Shonan guidelines (Sonnemann and Vigon 2011), pointed out as the reference for definitions according to the scientific selection procedure of (Schaubroeck et al. 2021c). Attributional LCAs can be considered as “normative”, as the linking of unit processes to the systems are based on a normative rule (Sonnemann and Vigon 2011).
- **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 analysed 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 practice, standardized LCA approaches rarely apply a purely attributional or consequential perspective (Schrijvers et al. 2016b). Therefore, in the following sections of the report, we refer to attributional LCA as “normative” LCA, which apply normative rules to determine which impacts are attributable to which products. Normative LCA approaches aim to assess a Product’s Environmental Footprint (PEF), based on agreed-upon rules among select stakeholders, which can be representative from governmental institutions (e.g. the Product Environmental Footprint (PEF) Guide ((European Commission 2021)), industry associations (e.g. EN 15804 (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 “how the environmental impacts of a product should be assessed”. They are written down in a standard or guideline, which further defines methodological choices beyond or besides the framework of ISO 14040-14044. 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).

11.2.2.3 *Consideration of upstream and downstream life cycles in the study scope*

Whereas circularity strategies may affect processes across different product life cycles, different allocation processes apply a different scope with regard to the processes that are evaluated within the assessment:

- Coverage of a “single life cycle”, with only the processes considered that are directly involved in the provision of a product’s function (such as in the cut-off approach)
- Consideration of “adjacent life cycles”, i.e. the consideration of processes directly involved in the provision of the function of the product that provides waste for valorisation (the preceding upstream life cycle) or that uses a valorised flow (the subsequent downstream life cycle).
- Coverage of “all life cycles”, finite or infinite, where the product system covers all life cycles/loops in

the product system. This may refer to upstream life cycles (e.g. historical cascades) and/or downstream life cycles (e.g. future cascades).

Note that certain methods in theory do not have cutoffs, e.g. consequential LCA or attributional LCA, but in practical modelling frameworks, e.g. cutoff at “adjacent life cycles” in ecoinvent are commonly applied. The differentiation if “adjacent” versus “all life cycles” has rarely been regarded in literature. Bringing this prominently forward, is a main strength of this work.

11.3 Selection of modelling methods for circularity strategies

11.3.1 LCA methods

Within this Goal & scope context, we identified the following LCA methods of interest to analyze:

- Product-based LCA:
 - Normative/standard LCA:
 - Product Environmental Footprint (PEF) Guide (EU commission 2021)
 - EN 15804+A2:2019 (CEN 2012; AFNOR 2022)
 - Allocation at the Point of Substitution (APOS) (Schrijvers et al. 2021a)
 - Consequential LCA
 - Consequential LCA as described by (Weidema 2003; Weidema et al. 2009, 2013; Schrijvers et al. 2021b)
- System/process-based LCA:
 - Interpretations of (Schrijvers et al. 2020; Schaubroeck et al. 2021a), as there is no standard, besides ISO 14040-14044, that exist that follows this focus.

There are more approaches of interest or that could be analyzed, but we selected these because of their prominence (PEF & EN), scientific consistency (attributional & consequential) and completeness (system-based LCA). These selected methods are further explained in the respective sections.

11.3.2 Stand-alone Circularity Indicators

The Material Circularity Indicator (MCI) assesses a product by evaluating the degree to which linear resource consumption is reduced, and restorative processes are enhanced for its constituent materials. It also considers the product's longevity and intensity of use in comparison to industry average standards. The calculation of the MCI indicator takes into account three primary product attributes: the mass of virgin materials used in production, the amount of unrecoverable waste associated with the product, and a utility factor that reflects the duration and intensity of the product's usage. The calculation initially determines the virgin feedstock and unrecoverable waste, followed by the integration of the utility factor, producing a score on a scale from 0 to 1 (Ellen Macarthur Foundation, 2019).

Rooted in the principles of the circular economy outlined in the development of the MCI, the Critical Transition indicators (CTI) emerged to address the need for a comprehensive, quantitative approach to measure circularity across entire companies, business units, or product groups. These indicators provide a framework that complements the assessments and tools currently employed by organizations. Expanding upon material flows, the Critical Transition Indicators (CTI) integrate water usage, renewable energy, and business value into their scope, offering a multidimensional view of a company's circular performance. However, unlike the MCI the CTI does not provide a final range between 0-1, but instead a combination of quantitative analysis of material flows and other resource usage, often with a scorecard approach that allows for estimates and assumptions based on the best available data (WBCSD, 2022).

The ISO 59020/2024 is an international standard which provides a structured approach to measure and assess circularity performance and sustainability impacts based on standard indicators and complementary methods at the organizational level. The standard outlines specific requirements and methodologies for assessing circularity, including key performance indicators (KPIs) and reporting structures. This standard approach is more formalized, requiring rigorous data collection and reporting in line with established international guidelines (ISO 59020, 2024).

11.4 Identification of circularity parameters

In summary, while all three frameworks promote circularity, the MCI is product-focused, CTI offers a more organizational and multidimensional approach, and ISO 59020:2024 provides a global, standardized framework for assessing and reporting circular economy practices at the organizational level. Identification of circularity parameters. From the methods presented in the previous section, “circularity parameters” are extracted. In this report, circularity parameters refer to aspects related to circularity that may be quantified or qualitatively assessed, for example, the recycled content of a product. For each method, an overview is provided on which circularity parameters are covered by the method. When a circularity parameter is “covered”, it means that a change in the value of this parameter (such as increased recycled content) will result in a change in the assessment result, when the method is applied.

From the analysis of each method, the following list of circularity parameters is established:

- Recycled content
- End-of-life recycling rate
- End-of-life energy recovery rate
- Quality degradation of recycled material
- Market situation (i.e. level of demand (high/low)) of a consumed recycled material
- Market situation (i.e. level of demand (high/low)) of a produced recycled material
- Potential uses of a produced recycled material (considering functionality and quality requirements)
- Market situation of produced recovered energy
- Market situation of consumed recovered energy
- Reuse rate in closed loop
- Environmental impacts of the recycling process for the recycled content
- Environmental impacts of the recycling process at the end of life
- Environmental impacts of the consumed primary raw material
- Environmental impacts of the substituted production of primary raw materials
- Environmental impacts of the energy recovery process
- Environmental impacts of the substituted energy source
- Environmental impacts of waste disposal without energy/raw material recovery
- Efficiency of the energy recovery process
- Energy content of material
- Multiple recycling loops in cascades
- Downstream effects of recycling in the subsequent life cycle, beyond the substitution of primary raw materials (e.g. differences in transport, use and EoL)
- Efficiency of the recycling process at the EoL
- Fraction of the product being collected to go into a composting process
- Efficiency of the recycling process for the recycled content

- Average lifetime of a product or material relative to an industry average
- Fraction of biological materials used which originate from Sustained Production
- Fraction of the product being collected for recycling at EoL
- Fraction of the product going to component reuse
- Fraction of the product comprising biological materials from Sustained Production going to energy recovery
- Average number of cycles of a product or material for the defined use phase relative to an industry average (Examples: number of cycles a washing machine can actually run in the defined use phase, compared to an industry average washing machine")
- Number of times a product is hired (multiple consumers during its use phase)
- Mass of unrecoverable waste of product going into landfill, waste to energy
- Mass of unrecoverable waste generated during the recycling process at EoL
- Mass of unrecoverable waste generated during the recycling process for the recycled content
- Reused content
- Actual recovery rate relative to the theoretical recovery potential
- Renewable material content
- Per cent of water demand that is derived from circular sources -Circular sources meaning that it either has a prior use or natural renewability
- Share of water consumed in process and operations that leaves the infrastructure for reuse by another organisation, or it is returned to the water source with the same/better quality
- On-site water circulation (reuse & recycle) (number of times the company uses the average drop of water onsite before it leaves the facility as outflow)
- Share of energy consumed that is renewable energy
- Percent from the total material/product which is considered to be a critical raw material (This can be assessed by using raw material lists identified by the European Union or the US national list of 50 critical mineral commodities, etc)
- Refurbishing rate
- Remanufacturing rate
- Material productivity (Ratio of revenue generated by total mass of all linear resource inflows)
- Resource intensity index (Ratio of the increase in resource consumption to the increase of gross domestic product (GDP) over a period of time)
- Impacts of a substituted waste treatment process
- Impacts of a substituted valorisation process

This list provides an overview of circularity parameters covered by at least one method. In the following section, each method is compared to this list. Based on this, the comprehensiveness of the assessment method to assess a circularity strategy is assessed, and potential complementary assessment methods are identified.

12 ASSESSMENT OF LCA METHODS TO MODEL CIRCULAR PRODUCT SYSTEMS

12.1 Product Environmental Footprint Guide

12.1.1 Introduction to the methodology

Within the Product Environmental Footprint (PEF) Guide, the environmental footprint is assessed for a single product life cycle stage. Impacts of the end-of-life treatment of a waste and benefits of waste valorisation are shared between the supplier of the waste and the user of the valorised material, following the Circular Footprint Formula (CFF).

Material

$$(1 - R_1)E_V + R_1 \times \left(A \times E_{\text{recycled}} + (1 - A)E_V \times \frac{Q_{\text{Sin}}}{Q_p} \right) + (1 - A)R_2 \times \left(E_{\text{recyclingEoL}} - E_V^* \times \frac{Q_{\text{Sout}}}{Q_p} \right)$$

Energy

$$(1 - B)R_3 \times (E_{\text{ER}} - \text{LHV} \times X_{\text{ER,heat}} \times E_{\text{SE,heat}} - \text{LHV} \times X_{\text{ER,elec}} \times E_{\text{SE,elec}})$$

Disposal

$$(1 - R_2 - R_3)E_D$$

Figure 18. Circular Footprint Formula separated in terms of Material, Energy, and Disposal (European Commission 2021).

Table 11. Parameters of the Circular Footprint Formula and their explanation (EU commission 2021).

Parameter	Explanation	Additional notes
A	Allocation factor of burdens and credits between supplier and user of recycled materials.	Reflects the market situation of recycled materials. Values are 0.2, 0.5, or 0.8 to always capture both aspects of recycling (recycled content and EoL recycling). Values of 1 and application-default are reported for cradle-to-gate studies. For composting, A = 0.5.
B	Allocation factor of energy recovery processes. It applies both to burdens and credits.	Default value of 0, unless another appropriate value is available in Part C of Annex II
Q_{Sin}	Quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.	Relative quality is determined based on economic or physical aspects.
Q_{Sout}	Quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.	Relative quality is determined based on economic or physical aspects. This parameter is only used if $E_v = E^*v$. In other cases, differences in quality are captured by E^*v .
Q_p	Quality of the primary material, i.e. quality of the virgin material.	
R_1	It is the proportion of material in the input to the production that has been recycled from a previous system.	
R_2	It is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall	

Parameter	Explanation	Additional notes
	be measured at the output ⁷ of the recycling plant.	
R_3	It is the proportion of the material in the product that is used for energy recovery at EoL.	Includes incineration with energy recovery, production of solid recovered fuel, and anaerobic digestion.
E_{recycled} (E_{rec})	Specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.	Modelling is done up to the point of substitution ⁸ .
$E_{\text{recyclingEoL}}$ (E_{recEoL})	Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.	Modelling is done up to the point of substitution.
E_v	Specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material.	
E_v^*	Specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material assumed to be substituted by recyclable materials.	If $E_v^* \neq E_v$, E_v^* should reflect the substituted virgin material in terms of “how long” and “how well”.
E_{ER}	Specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.).	
$E_{\text{SE,heat}}$ and $E_{\text{SE,elec}}$	Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.	
E_D	Specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.	

⁷ This has been criticized by (Schrijvers et al. 2021b), who argue that R_2 should be measured at the start of the recycling chain (i.e. the collection share). Otherwise, waste treatment of recycling losses are double counted in both E_D and E_{recEoL} .

⁸ The point of substitution should be identified in correspondence to the process where input flows come from 100% primary sources and 100% secondary sources. In some cases, the point of substitution may be identified after some mixing of primary and secondary material flows has occurred (European Commission 2021).

Parameter	Explanation	Additional notes
$X_{ER,heat}$ and $X_{ER,elec}$	The efficiency of the energy recovery process for both heat and electricity.	
LHV	Lower heating value of the material in the product that is used for energy recovery.	

12.1.2 Circularity challenges and data needs

Table 12 gives an overview of how the PEF method addresses challenges to model circularity strategies in biobased sectors. Furthermore, an overview of recommendations provided by the PEF Guide on data collection is given in Table 13.

Table 12. Addressing of circularity challenges by the PEF method. From (European Commission 2021), emphasis added to quotes.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	“Currently, credits associated with temporary and permanent carbon storage and/or delayed emissions shall not be considered in the calculation of the climate change indicator. This means that all emissions and removals shall be considered as emitted ‘now’, and there is no discounting of emissions over time (in line with EN ISO 14067:2018). Developments will be considered in order to keep the method updated with scientific evidence and expert-based consensus.”
Allocation of biogenic carbon and carbon storing capability	Only biogenic methane is characterized, other emissions have a characterization factor of zero. No mentioning is made of a transfer of emission across different life cycles, so it is assumed that emissions are modelled in the process in which the uptake or emission takes place.
Addressing the longevity of products	“[In the situation of lifetime extension to a product with the original product specifications (providing the same function) due to reuse or refurbishment,] the product lifetime is extended and shall be included in the FU and reference flow. The user of the PEF method shall describe how reuse or refurbishment is included in calculating the reference flow and the full life-cycle model, taking into account the ‘how long’ of the FU.” A formula is provided to calculate the reuse rate or the number of reuses: $\text{Number of reuses} = \frac{1}{100\% - (\% \text{ reuse rate})}$ LCI of raw material acquisition, cradle-to-gate transport, and EoL waste treatment are divided by the number of reuses. LCI of transport between the producer and user (including return trips) and preparations for reuse are added as they take place.
Multiple loops, finite loops, steady/non-steady state	“If the reuse/refurbishment of a product results in a product with different product specifications (providing another function) , this

	shall be considered as part of the CFF, as a form of recycling. Old parts that were changed during refurbishment shall be modelled under the CFF. In this case, reuse/refurbishment activities fall under the ErecEoL parameter, while the alternative function provided (or the avoided production of parts or components) falls under the E*v parameter.”
Cascading chains	The CFF seems limited to consider only adjacent life cycles, i.e. 1 preceding and 1 subsequent life cycle, and only consider the avoided primary <i>materials</i> in the subsequent life cycle. The recyclability at the end of life of the second life cycle seems to fall outside the scope of the CFF.

Table 13. Overview of potential data sources for a selection of circularity parameters in the PEF Guide (extracted from (European Commission 2021)).

Circularity parameter	Parameter method	in	Potential data sources	Strategy in case of data gaps
Recycled content	R1		Based on 1) company-specific data, or 2) default application-specific data from Part C of Annex II ⁹	Set to 0 if no application-specific data are available
End-of-life recycling rate	R2		Recyclability must first be evaluated according to defined criteria ¹⁰ . Then, R2 is based on 1) company-specific data, or 2) default application-specific or material-specific data from Part C of Annex II	Set to 0 if no application or material-specific data are available
End-of-life energy recovery rate	R3		Rate based on 1) company-specific data, or 2) default secondary data	Use new values based on statistics or other data sources, or set to 0
Quality degradation (assessed by price ratio)	Qsin/Qp and Qsout/Qp	and	Part C of Annex II (paper and cardboard)	Relative quality is determined based on economic or physical aspects.
Market situation of recycled material	A		Part C of Annex II	If no material-specific A-value is available, a value of 0.5 shall be applied

⁹ <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html>

¹⁰ Criteria to evaluate recyclability (EU commission 2021): 1) The collection, sorting and delivery systems to transfer the materials from the source to the recycling facility are conveniently available to a reasonable proportion of the purchasers, potential purchasers and users of the product. 2) Recycling facilities to accommodate the collected materials exist. 3) Evidence is available to show that the product for which recyclability is claimed is being collected and recycled.

Market situation of recovered energy	B	Part C of Annex II	Default value is 0
Reuse rate (company-owned products) in closed loop	NA	Supply-chain specific data based on past experience or based on future estimations	In case no data are available: conservative assumptions on average number of rotations, lifetime of product pool, average percentage of loss per reuse cycle
Reuse rate (third party operated pools) in closed loop	NA	Not specified	Use default values from PEF guide (of bio-based materials, only wooden pallets are mentioned)

12.1.3 Supplier of recovered material/energy at end of life

12.1.3.1 *Research questions*

From the perspective of the supplier of a recycled or recovered material/energy flow, the following research questions can be addressed by the application of the PEF Guide:

- For what environmental impacts is (the user of) my product accountable?
- Should I make (part of) my product recyclable/recoverable at the end of life reduce my/the product's user's accountability for impacts?

These questions may be asked by actors that are involved solely in the first life cycle of the product, such as the manufacturer of the product, or the user of the product.

12.1.3.2 *Functional unit*

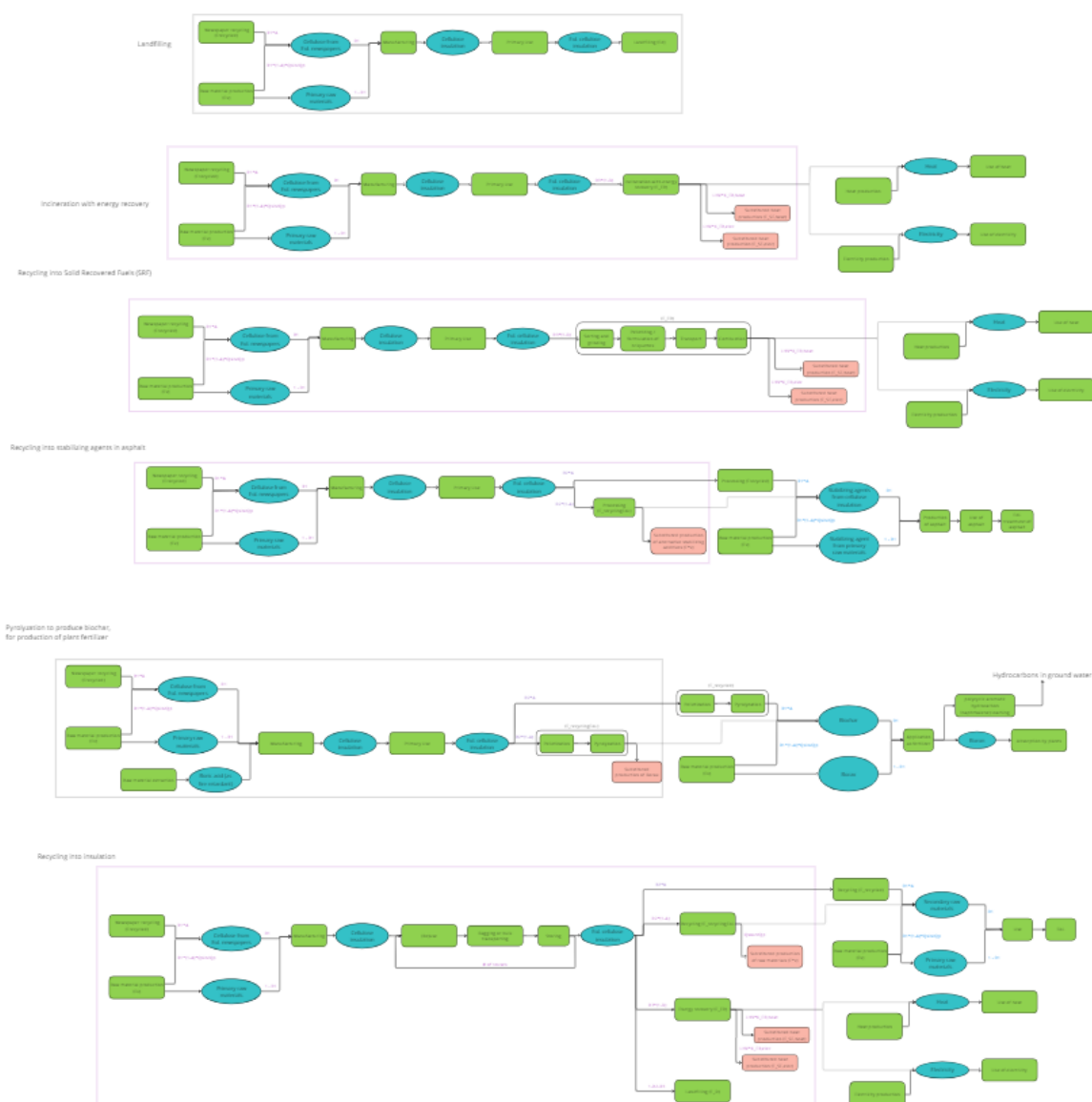
According to the PEF Guide, a functional unit is established, in which the following properties are described:

- What? *Example: Cellulose-based thermal insulation material for a residential building*
- How much? *Example: For the thermal insulation of 100 m²*
- How well? *Example: Provision of a thermal resistance of 5 m².K/W*
- How long? *Example: During 50 years*
- Reference flow: amount of product needed to fulfil the define function. *Example: 40 kg of cellulose-based insulation material*

This functional unit is applied for cradle-to-grave studies. In a cradle-to-gate study, a declared unit can be formulated, which may coincide with the reference flow. This declared unit may serve in future LCA studies with different applications of a same final product.

12.1.3.3 *System boundaries*

Figure 19 shows which processes are included within the system boundaries of the different scenarios in the illustrative example of cellulose insulation. The inclusion of parameters near the arrows includes the extent to which the connected processes are modelled. For example, the factor $R1 \cdot A$ shows that, with a recycled content ($R1$) of 100%, an A -value of 0.5 and a quality factor (Q_{sin}/Q_p) of 1, the recycling process ($E_{recycled}$) is modelled for 50% of the total input of raw materials, whereas the primary production process (E_v) is modelled for another 50%.



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Figure 19. System boundaries of different scenarios for cellulose insulation, from the perspective of the 1st life cycle of the insulation, according to the PEF Guide. The dotted arrows indicate flows of material/energy that are modelled by alternative processes (indicated by solid arrows).

12.1.3.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

All scenarios: It was assumed that the cellulose used for insulation was supplied from end-of-life newspapers. As this is a secondary raw material, the term referring to the recycled content (R1) in the CFF is applied to all scenarios. According to Part C of Annex II, 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 of the production of cellulose from EoL newspapers is modelled for 50% of the total quantity of cellulose used. The remaining share of consumed cellulose is modelled by a primary production process. This may refer to

the primary production of cellulose, or another primary raw material that can be used in the same application. This may be specified in an applicable PEFCR document. If there are quality differences between recycled cellulose and the primary alternative, the primary production process represents is modelled for a corresponding lower (or higher) flow of raw materials.

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

Recycling into stabilizing agents in asphalt: The material-specific value of $A = 0.5$ for cellulose insulation is applied to the recycling of insulation at the end of life. This means that the flow of EoL cellulose is only for 50% modelled by further processing into stabilizing additives, and the substitution of primary additives is only modelled for 50%. The specific primary additive that is substituted and reflected by E^*v is determined by The quantity of primary additives substituted is based on “how well” the additives displace one another. The remaining 50% of the flow of EoL cellulose insulation is modelled by the “cut-off” principle, i.e. no further processing is modelled within the boundaries of the first life cycle.

Recycling into biochar for the 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 only for 50% modelled by further processing into biochar, and the substitution of Borax is only modelled 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 leads to the avoidance of the leaching of Borax during the application phase of the fertilizer, and to the increase of the leaching of naphthalene. This downstream effect is not included in the CFF. The remaining 50% of the flow of EoL cellulose insulation is modelled by the “cut-off” approach, i.e. no further processing is included within the boundaries of the first life cycle.

Reuse into insulation: Reuse into the same functionality extends the product’s lifetime. Each use cycle is accountable for impacts related to use and preparation for reuse. The impacts related to 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 attributed to a single use 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 be applicable to the insulation material after the final use scenario, such as landfilling, incineration, or recycling into stabilizing agents for asphalt.

12.1.4 User of recovered material/energy

12.1.4.1 *Research questions*

From the perspective of the user of a recycled or recovered material/energy flow, the following research questions can be addressed by the application of the PEF Guide:

- For what environmental impacts is (the user of) my product accountable?
- Should I use recycled/recovered raw materials/energy in my product to reduce my/the product’s user’s accountability for impacts?

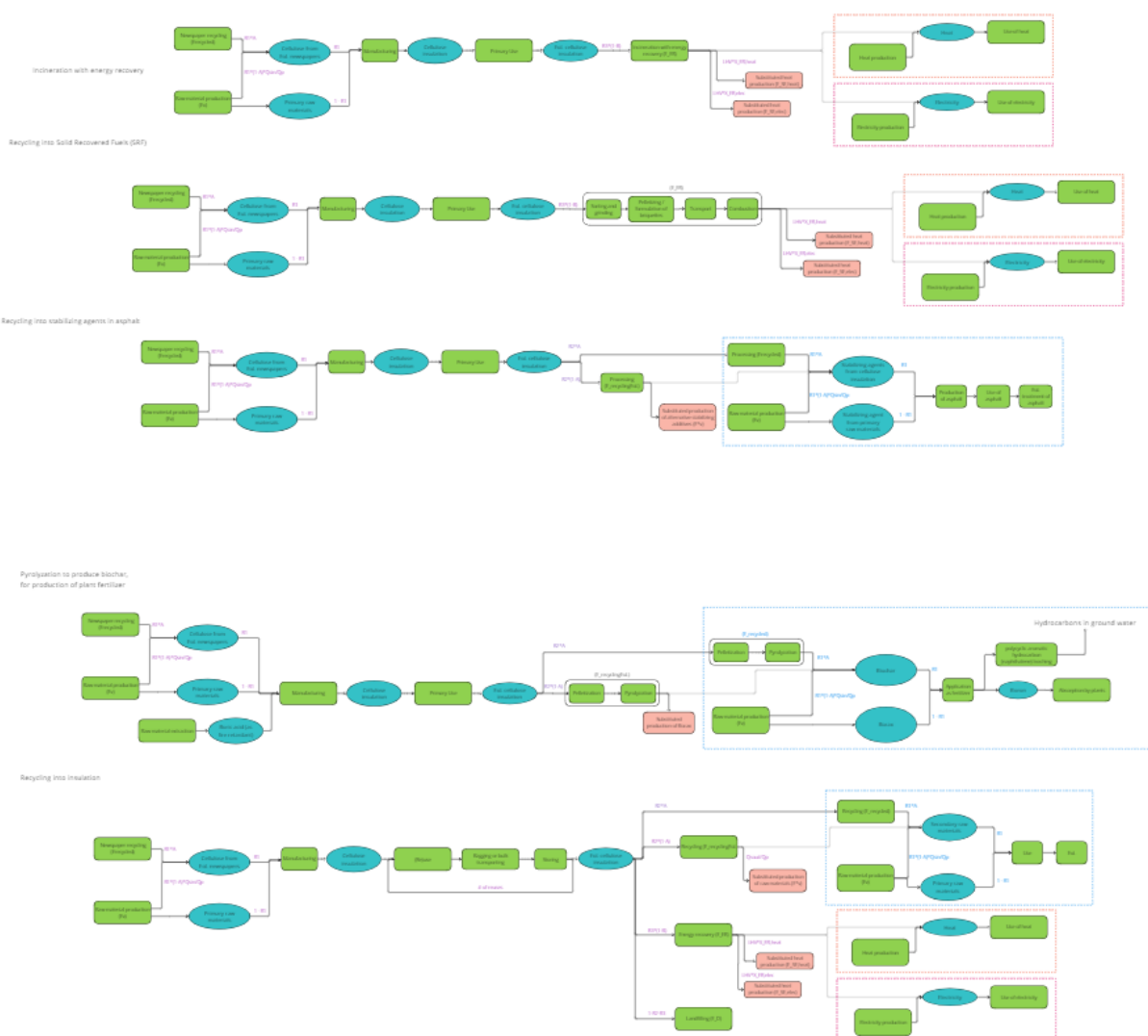
These questions may be asked by actors that are involved solely in the second life cycle of the product, such as the manufacturer of the product that uses a recycled material, the manufacturer that uses recovered energy, or the user of the final product.

12.1.4.2 Functional unit

The functional unit for the user of the secondary raw material or energy is scenario-specific, as the scenarios provide different outputs for a subsequent life cycle. The declared unit or reference flow could therefore be, for example, a certain quantity of energy used, a certain quantity of boron needed for fertilization of plants, or a quantity of asphalt produced.

12.1.4.3 System boundaries

The system boundaries of the second life cycle of the illustrative example, in which the EoL cellulose insulation is valorised, are shown for the different scenarios in Figure 20.



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Figure 20. System boundaries of different scenarios for cellulose insulation, from the perspective of the 2nd life cycle in which the EoL cellulose insulation is valorised, according to the PEF Guide.

12.1.4.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

Incineration / production of SRF: The impacts of energy valorisation, and the benefits of the substituted energy sources are already modelled in the first life cycle, in which energy was recovered at the end of life. The CFF does not include a term for *using* recovered energy, which would be relevant if parameter B would be different than 0. Therefore, it is not clear from the CFF how the consumption of recovered energy should be modelled. The most consistent approach, in line with the first life cycle, would be to model the consumption of heat and electricity by the energy production from the same sources that were modelled to be substituted in the first life cycle. However, the modelling of energy use as prescribed by the PEF Guide allows for the modelling according to contractual agreements. If there would be a contractual agreement with a provider of recovered energy, the recovery process and potential benefits of using recovered energy would be double counted between 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 of $A = 0.5$ for cellulose insulation is applied to stabilizing agents 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 for 50% modelled by the recycling process of EoL insulation material, and by 50% modelled by the use of a stabilizing agent from primary sources. Also here, there is no explicit guidance on how the specific primary additive that is substituted and reflected by E_v 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 the 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 only for 50% modelled by the production of biochar from EoL cellulose insulation. The remaining 50% of this biochar input is modelled as the production of Borax. The quantity of Borax that is modelled 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 highlighted that the use of Borax for this application results in the leaching of Borax to the environment. However, as Borax is not actually used (but only biochar), only the leaching of particles associated with biochar is modelled in the use phase (e.g. hydrocarbons in ground water). Therefore, **there is a mismatch between the modelling of consumed raw materials and associated impacts downstream in the life cycle**, due to the fact that the CFF does not include a term for downstream effects for using a recycled material instead of a primary material.

Reuse into insulation: Reuse into the same functionality extends the product’s lifetime. Therefore, all the reuse cycles are still considered within the “first life cycle” of the insulation. The EoL insulation material reaches a second life cycle, only once it is finally recycled into a different application, or when it is valorised energetically after the final reuse cycle. The user of the valorised material/energy in the second life cycle models the consumed valorised flows as described in the above scenarios.

12.1.5 Limitations of the PEF Guide

The following limitations have been observed regarding the PEF Guide:

- Collection rate and recycling efficiency rate are merged into one parameter, leading to erroneous calculations of recycling losses (Schrijvers et al. 2021b)
- No parameter is included for *using* recovered energy, resulting in potential modelling inconsistencies between supplying and using recovered energy
- Mandatory modelling of primary raw material use due to restricted options for parameter A, even if this is not corresponding with reality
- Additional guidance is needed to identify the (substituted) primary raw material source
- Additional guidance is needed to identify the (substituted) energy production source
- Only substitution of primary materials is modelled, downstream effects of this substitution (e.g. differences in transport, use, or EoL) are not considered. This especially results in strange results for the user of a recycled material, that needs to model primary production, without modelling the consequences of using a primary material (see for example the leaching of borax in the biochar scenario).
- Final disposal of waste after multiple reuse cycles needs to be modelled, although the relevant processes may be unknown.
- 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.

12.1.6 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by the PEF Guide (as analysed in Table 13), the following circularity strategies may result in a beneficial effect of the product assessment using the PEF Guide:

- Increase recycled content
- Increase EoL recycling rate
- Increase EoL energy recover rate
- Minimize quality degradation
- Use recycled materials with low economic value/low demand
- Produce recycled materials with high economic value/high demand
- Increase the functional characteristics of the produced recycled material at the end of life
- Produce recovered energy with high economic value/high demand
- Increase reuse
- Decrease impacts of the recycling process of the recycled content
- Decrease impacts of the recycling process at the end of life
- Decrease impacts of primary raw material production
- Increase impacts of substituted primary raw material production
- Decrease impacts of the energy recovery process
- Avoid primary energy sources with high environmental impacts
- Decrease impacts of waste disposal
- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Increase the efficiency of the recycling process at the EoL
- Increase the fraction of an EoL material that is collected for composting
- Increase the efficiency of the recycling process for the recycled content

- Increase the fraction of biological materials used which originate from Sustained Production
- Increase the fraction of a material collected for recycling at EoL
- Increase the fraction of a material collected for component reuse
- Increase the average number of uses of a material
- Increase the number of different users of a product during its use phase (via sharing/leasing)
- Decrease the mass of unrecoverable waste going to landfilling
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Increase the share of reused content in a product
- Increase the share of renewable content in a product
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use
- Increase the refurbishing rate
- Increase the remanufacturing rate

However, other circularity strategies may not result in noticeable benefits while applying the PEF Guide, as the PEF Guide does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 14 can be used to provide this complementary information.

Table 14. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by the PEF Guide.

Circularity strategies not covered by the methodology	Comparative LCA using the PEF Guide	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Increase the lifetime of a product	Yes				Yes	Yes	Yes, optionally
Avoid waste treatment with high environmental impacts	Yes		Yes				
Avoid other valorisation processes with high environmental impacts	Yes		Yes				
Use recovered energy with low economic value/low demand		Yes	Yes				
Enable the use of a material in multiple loops in cascades		Yes	Yes	Yes		Yes	
Decrease impacts of downstream effects due to the substitution of a primary material			Yes	Yes			
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery					Yes	Yes	
Use less critical raw materials						Yes, optionally	
Increase the revenue generated relative to the total mass of linear resource inflows						Yes	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP							Yes, optionally

12.2 EN 15804

12.2.1 Introduction to the methodology

The EN 15804 standard (AFNOR 2022) formulates Product Category Rules (PCR) for the construction sector. These rules are to be followed in the development of Environmental Product Declarations in this sector. Due to the frontrunning position of the construction sector in the application of LCA (pushed by regulations), this PCR document has inspired the practice of LCA in other sectors as well.

Within EN 15804, a product's life cycle is split into Modules A to D, of which only Module A is mandatory for compliance with the standard:

- Modules A1-A3: Product stage
 - o Primary raw material extraction and processing and the processing of secondary material input are modelled in Module A1. These processes do not include processes that are part of the waste processing in the previous product system.
 - o Energy recovery and other recovery processes from secondary fuels, excluding processes that are part of waste processing in the previous product system are also included in Module A1.
- Modules A4-A5: Construction process stage
- Modules B1-B7: Use stage
- Modules C1-C4: End-of-life stage
 - o De-construction/demolition, transport to waste processing, waste processing for reuse, recovery (including incineration), and/or recycling, and disposal are modelled in Modules C1-C4
- Module D: Benefits and loads beyond the system boundary
 - o Reuse, recovery and/or recycling potentials, expressed as net impacts and benefits, are modelled in Module D for outputs of Modules A4-A5 and B-C.

The boundary between Module C and Module D is put at the “end-of-waste state”. This state is reached, when a waste complies with the following criteria (AFNOR 2022):

- *The recovered material, product or construction element is commonly used for specific purposes;*
- *A market or demand, identified e.g. by a positive economic value, exists for such a recovered material, product or construction element;*
- *The recovered material, product or construction element fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products;*
- *The use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.*

NOTE: The “specific purpose” in this context is not restricted to the function of a certain product but can also be applied to a material serving as input to the production process of another product or of energy.

A few additional specifications are mentioned that must be met to reach the end-of-waste state:

- For waste for energy recovery, the energy recovery process has an energy efficiency rate higher than 60%
- The recovered material does not contain hazardous substances that surpass regulatory limits.

Module D can contain the benefits provided by substituting primary production of functional equivalent materials. A justified value-correction factor is applied if functional equivalence is not reached. Processes that

are substituted are the current average production processes. Loads and benefits are only calculated for the *net* output of secondary material or fuel (i.e. the output of these flows, minus the input into each sub-module).

12.2.2 Circularity challenges and data needs

Table 15. Addressing of circularity challenges by the EN 15804 method.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	Not addressed
Allocation of biogenic carbon and carbon storing capability	The emissions of CO ₂ provided from biogenic carbon must be distinguished from other carbon sources in Module C4 (i.e. end-of-life waste treatment)
Addressing the longevity of products	Reuse is, similar to recycling, modelled in Module D. The fact that no additional processing may be needed reduces potential impacts of Module C and/or Module D. Benefits of substituting a primary raw material are included in Module D.
Multiple loops, finite loops, steady/non-steady state	Potential quality degradation in comparison with the substituted primary material is considered by the inclusion of a value-correction factor. However, the concrete differences between future recycling possibilities are not quantified.
Cascading chains	Open-loop recycling for 1 subsequent life cycle is considered.

12.2.3 Supplier of recovered material/energy at end of life

12.2.3.1 *Research questions*

The same research questions can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.3.1.

12.2.3.2 *Functional unit*

The same functional unit can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.3.2.

12.2.3.3 *System boundaries*

Figure 29 shows which processes are included within the system boundaries of the different scenarios in the illustrative example of cellulose insulation.

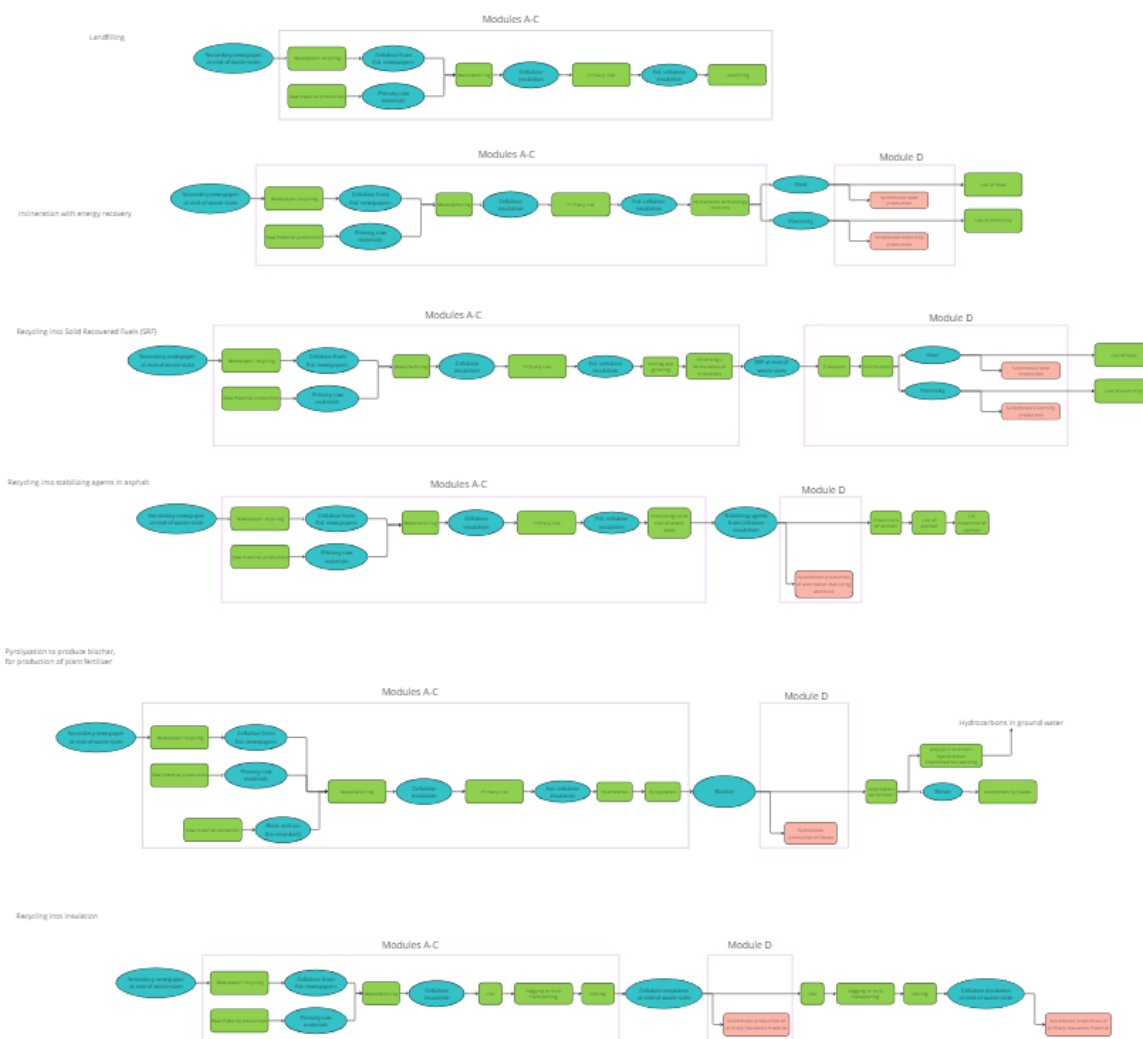


Figure 21. System boundaries of different scenarios for cellulose insulation, from the perspective of the 1st life cycle of the insulation, according to EN 15804. The dashed lines indicate the different modules according to the EN 15804 approach.

12.2.3.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

All scenarios: It was assumed that the cellulose used for insulation was supplied from end-of-life newspapers. The recycled content is modelled 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 modelled in Module A. Waste treatment and/or recycling processes at the end of life are modelled up to the end-of-waste state of a produced valorised 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 modelled within Module C of the first life cycle. Benefits of the substitution of alternative energy production processes are modelled in Module D. The avoided energy source may be modelled as the energy source that is actually substituted. If this is unknown, the country-specific energy mix is used of the country in which the substitution takes place (AFNOR 2022).

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

Recycling into stabilizing agents in asphalt: Recycling of the EoL cellulose is modelled 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 added to Module D. Module D only contains 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 the use as fertilizer: The end-of-waste stage in this scenario is determined at the production of biochar. Therefore, palletisation and pyrolyzation are included in Module C. However, it might be justifiable to determine the end-of-waste state after the palletisation process. In the latter case, pyrolyzation would become part of Module D. In the current definition of the system boundaries, Module D only includes the benefits of substituting the production of Borax. Any additional downstream consequences of substituting Borax by biochar, such as differences in leaching, are outside the scope of the assessment.

Reuse into insulation: The end of life 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 is modelled in Module D.

12.2.4 User of recovered material/energy

12.2.4.1 *Research questions*

The same research questions can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.4.1.

12.2.4.2 *Functional unit*

The same functional unit can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.4.2.

12.2.4.3 *System boundaries*

The system boundaries of the second life cycle of the illustrative example, in which the EoL cellulose insulation is valorised, are shown for the different scenarios in Figure 22.

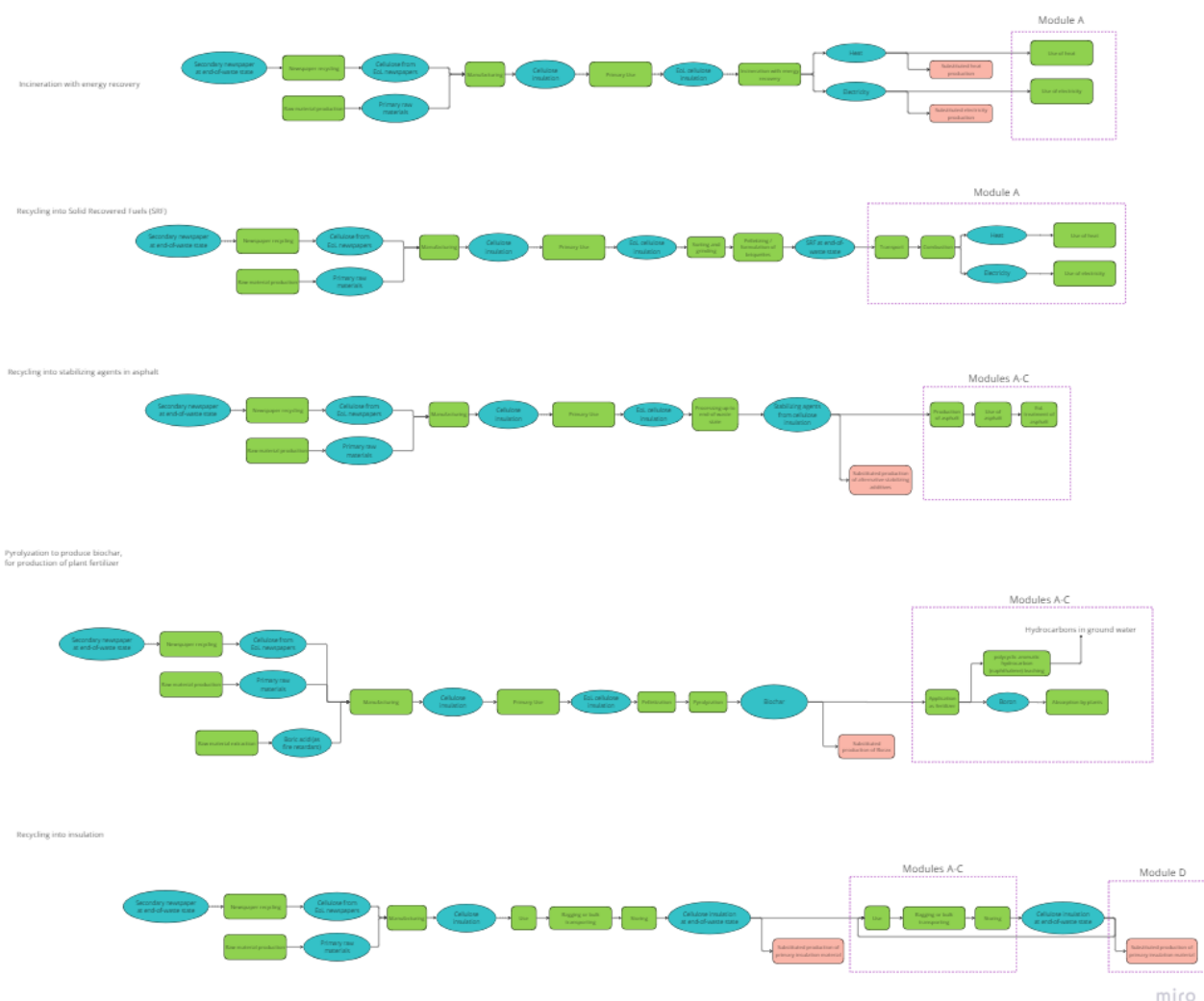


Figure 22. System boundaries of different scenarios for cellulose insulation, from the perspective of the 2nd life cycle in which the EoL cellulose insulation is valorised, according to EN 15804.

12.2.4.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

Incineration with energy recovery: The impacts of incineration are already modelled in the first life cycle. The user of the recovered energy can use the recovered energy 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 where the stabilizing agent is produced, no further recycling processes are modelled by the user of the stabilizing agent, the product is burden-free.

Recycling into biochar for the 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 into insulation: In this example, no recycling/reuse steps are modelled by the 2nd user of the cellulose insulation material, as these have been modelled by the previous user. However, if at the end of life the insulation material is prepared for a 3rd reuse cycle, preparatory processes are modelled in Module C of the 2nd user. Benefits of reuse, by the substitution of a primary insulation material, are only modelled for the *net* output of reused insulation material, i.e. the quantity of reused insulation material made available at the end of life *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 modelled 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 2nd life cycle.

12.2.5 Limitations of EN 15804

The following limitations have been observed regarding EN 15804:

- Only substitution of primary materials is modelled, downstream effects of this substitution (e.g. differences in transport, use, or EoL) are not considered.
- 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.
- Determination of “end-of-waste state” may be difficult, where multiple interpretations and/or practices could lead to variation in the modelling.
- Technically, if only recycled materials are used as input, and no recycling takes place at the end of life, 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.

12.2.6 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by EN 15804, the following circularity strategies may result in a beneficial effect of the product assessment using EN 15804:

- Increase recycled content
- Increase EoL recycling rate
- Increase EoL energy recover rate
- Minimize quality degradation
- Increase the functional characteristics of the produced recycled material at the end of life
- Increase reuse
- Decrease impacts of the recycling process of the recycled content

- Decrease impacts of the recycling process at the end of life
- Decrease impacts of primary raw material production
- Increase impacts of substituted primary raw material production
- Decrease impacts of the energy recovery process
- Avoid primary energy sources with high environmental impacts
- Decrease impacts of waste disposal
- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Increase the efficiency of the recycling process at the EoL
- Increase the fraction of an EoL material that is collected for composting
- Increase the efficiency of the recycling process for the recycled content
- Increase the fraction of biological materials used which originate from Sustained Production
- Increase the fraction of a material collected for recycling at EoL
- Increase the fraction of a material collected for component reuse
- Increase the average number of uses of a material
- Increase the number of different users of a product during its use phase (via sharing/leasing)
- Decrease the mass of unrecoverable waste going to landfilling
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Increase the share of reused content in a product
- Increase the share of renewable content in a product
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use
- Increase the refurbishing rate
- Increase the remanufacturing rate

However, other circularity strategies may not result in noticeable benefits while applying En 15804, as this standard does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 16 can be used to provide this complementary information.

Table 16. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by EN 15804.

Circularity strategies not covered by the methodology	Comparative LCA using EN 15804	PEF Guide	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Increase the lifetime of a product	Yes					Yes	Yes	Yes, optionally
Avoid waste treatment with high environmental impacts	Yes			Yes				
Avoid other valorisation processes with high environmental impacts	Yes			Yes				
Use recycled materials with low economic value/low demand		Yes	Yes	Yes				
Produce recovered energy with high economic value/high demand		Yes	Yes	Yes				
Produce recycled materials with high economic value/high demand		Yes	Yes	Yes				
Use recovered energy with low economic value/low demand			Yes	Yes				
Enable the use of a material in multiple loops in cascades			Yes	Yes	Yes		Yes	
Decrease impacts of downstream effects due to the substitution of a primary material				Yes	Yes			
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery						Yes	Yes	

Circularity strategies not covered by the methodology	Comparative LCA using EN 15804	PEF Guide	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Use less critical raw materials							Yes, optionally	
Increase the revenue generated relative to the total mass of linear resource inflows							Yes	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP								Yes, optionally

12.3 Allocation at the point of substitution

12.3.1 Introduction to the methodology

Allocation at the point of substitution (APOS) is a partitioning method that is equally applicable to co-products, recycled materials, and recovered energy. The method had been introduced by (Weidema 2017), 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. By applying the same allocation method to co-products, recycled materials, and recovered energy, the APOS method is arguably more consistent with the requirements of ISO 14040/14044, compared to the PEF Guide and EN 15804. Furthermore, the consistent application of partitioning makes the APOS method purely attributional, where the PEF Guide and EN 15804 combine attributional and consequential elements, due to the inclusion of “substituted” processes (Schrijvers et al. 2016b).

According to (Schrijvers et al. 2021a), APOS is based on the following axioms and definitions, where some of the definitions are taken from ISO 14040/44, from other sources, or modified:

Axiom 1: A product is associated with the environmental impacts generated by the activities that are required in its life cycle.

Axiom 2: The environmental impacts of an activity are attributable to the products according to their contribution to the economic viability of this activity.

Table 17. Definitions of concepts used in the description of Allocation at the Point of Substitution (Schrijvers et al. 2021a).

Concept	Definition
Co-product	Any of two or more products produced by the same production system
Elementary flow	Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation
End of life	Stage which a product reaches once it ceases to be used for its intended use
Input	Product, material or energy flow that enters a unit process
Intermediate flow	Product, material or energy flow occurring between unit processes of the system being studied
Material for treatment	Input or output of a unit process that is not a product nor an elementary flow, such as an intermediate flow or a product at its end of life requiring additional treatment before being converted into elementary flows and/ or a product
Output	Product, material or energy flow that leaves a unit process
Product	Any substance or object that fulfils the following requirements: a. The substance or object is commonly used for specific purposes; b. A market or demand exists for such a substance or object; and c. The substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products.
Product life cycle	Consecutive and interlinked stages that a product undergoes including raw material extraction, production, use, and treatment at its end of life

Product system	Collection of unit processes which has elementary flows, performs one or more defined functions, and models the life cycle of a product
Production system	Collection of unit processes which has elementary, and product flows, includes raw material acquisition or generation from natural resources, and models the production of one or more products
Secondary product	A product produced by the treatment system of a product at its end of life
Treatment system	Collection of unit processes converting one or more materials for treatment into elementary and product flows, which models the treatment of one or more materials for treatment
Unit process	Smallest element considered in the life cycle inventory analysis for which input, and output data are quantified

Axiom 1 helps in the definition of system boundaries of a product system, whereas Axiom 2 supports the application of economic allocation. The APOS method is, ideally, an acceptable allocation method among stakeholders that agree with the underlying axioms and definitions.

12.3.2 Circularity challenges and data needs

Table 18. Addressing of circularity challenges by the APOS method.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	Not addressed
Allocation of biogenic carbon and carbon storing capability	Carbon capture and emissions are modelled within the processes where they take place. These flows are subsequently partitioned among co-products of the production systems according to their relative economic revenue. Carbon uptake and emissions attributed to a recycled/recovered product are therefore not necessarily related to the carbon content of this product. This is explained by the understanding that the existence of a demand for a product result in a <i>responsibility</i> for these flows, even though the physical flows may not be <i>caused</i> by the product itself.
Addressing the longevity of products	If a product can be reused in different life cycles, each life cycle carries a partial accountability for impacts of production and preparation for reuse. The first user is responsible for a relatively higher share of impacts than the last user. Only the last user is accountable for impacts of final disposal. A different repartition of impacts may be possible with a revised definition of “end of life”.
Multiple loops, finite loops, steady/non-steady state	If a product has passed through multiple historical loops, impacts are partitioned among previous loops, resulting in a lower accountability for impacts. If a product is made available for another loop at the end of life, another partitioning action results also in lower impacts. However, future loops beyond the first subsequent user are outside the scope of the assessment. The APOS method is limited to all upstream (historical loops) and only one future subsequent loop.

	Average impacts can be calculated if loops are steady-state. If loops are different over time, all upstream loops need to be modelled one by one to assess the final inventory of a specific life cycle.
Cascading chains	Upstream cascades are assessed by modelling each previous life cycle one by one. Open-loop recycling is addressed by considering the relative revenue of the output material, rather than its functionality or application.

12.3.3 Supplier of recovered material/energy at end of life

12.3.3.1 *Research questions*

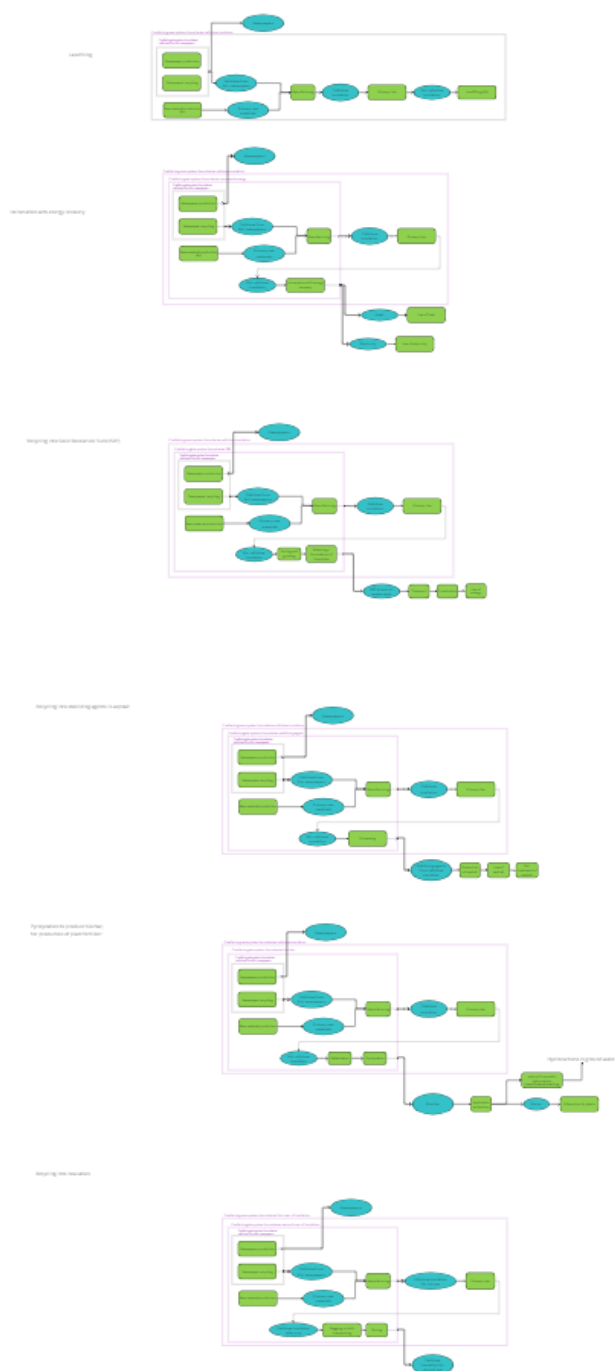
The same research questions can be addressed by APOS as by the PEF Guide, as presented in Section 12.1.3.1.

12.3.3.2 *Functional unit*

The same functional unit can be addressed by APOS as by the PEF Guide, as presented in Section 12.1.3.2.

12.3.3.3 *System boundaries*

The system boundaries of the first life cycle of the illustrative example, in which the EoL cellulose insulation is valorised, are shown for the different scenarios in Figure 22.



miro

Figure 23. System boundaries of different scenarios for cellulose insulation, from the perspective of the 1st life cycle in which the EoL cellulose insulation is valorised, according to the APOS approach. The dotted arrows indicate physical flows of material/energy, which are “overruled” by a restructuring of processes to establish the partitioned system. Thick solid arrows show the co-products of a joint production process, which are partitioned according to their relative economic revenue.

12.3.3.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

All scenarios: It was assumed that the cellulose used for insulation was supplied from end-of-life newspapers. To model this recycled content, it must be determined which environmental impacts are attributable to cellulose from EoL newspapers. Following Axiom 1, the processes that are required to make cellulose from EoL newspapers are the 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, the environmental impacts of this production system are partitioned between the newspapers and the cellulose insulation according to the relative economic revenue that they generate to this system.

Incineration with energy recovery: System boundaries are drawn to show the processes that are required to produce the recovered energy. Recovered heat and electricity are co-products of cellulose insulation. Partitioning is applied among these flows according to the relative economic revenue generated by these flows. As a consequence, cellulose insulation *and* recovered heat and electricity are partly accountable for the production of newspapers, newspaper recycling, 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 applied definition 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 among these flows according to the relative economic revenue generated by these flows. As a consequence, cellulose insulation *and* SRF are partly accountable for the production of newspapers, newspaper recycling, manufacturing of cellulose insulation, and the sorting, grinding, and pelletizing process. 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: System boundaries are drawn 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 among these flows according to the relative economic revenue generated by these flows. As a consequence, cellulose insulation *and* stabilizing agents are partly accountable for the production of newspapers, newspaper recycling, manufacturing of cellulose insulation, and the entire recycling process.

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

Reuse into insulation: In this scenario, the key question is how the end of life of cellulose insulation is defined – either after a first use, similar to EN 15804, or after all potential uses (e.g. 3 or 4 uses), such as in the PEF Guide. The definition of “end of life” in Table 17 gives room for both interpretations, as “intended use” may be specific to a building, or specific to the material itself. In Figure 23, the same interpretation as in EN 15804 is applied. Following this, the first and the second use of the cellulose insulation are both co-products of the

production system that contains the processes of cellulose manufacturing and preparation for reuse. In this interpretation, the first user of the insulation does not model the final disposal of the insulation (after e.g. 3 uses). This may be justified, as the final disposal is out of control of this first user and may take place after a long timeframe (e.g. 100 years considering the long lifetime of buildings). Furthermore, this interpretation allows for the consideration of quality loss over different reuse cycles, as the first use and the second use may not provide the same economic revenue (a material that has been used 3 times before may be cheaper than a new material).

12.3.4 User of recovered material/energy

12.3.4.1 Research questions

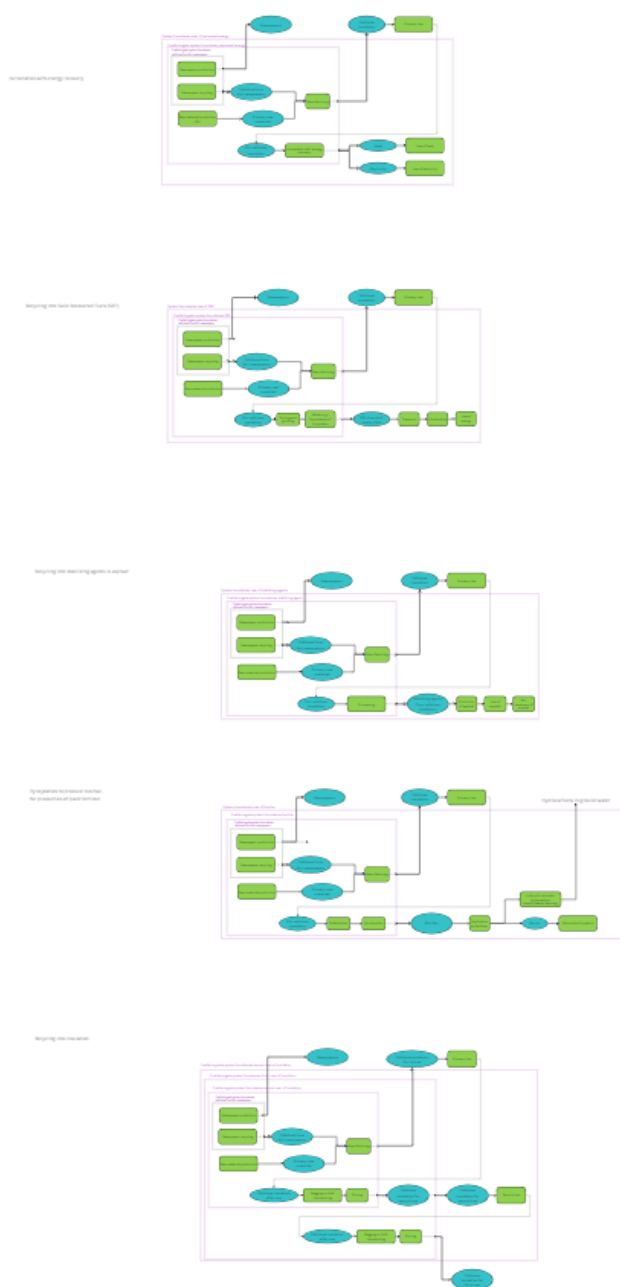
The same research questions can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.4.1.

12.3.4.2 Functional unit

The same functional unit can be addressed by EN 15804 as by the PEF Guide, as presented in Section 12.1.4.2.

12.3.4.3 System boundaries

The system boundaries of the second life cycle of the illustrative example, in which the EoL cellulose insulation is valorised, are shown for the different scenarios in Figure 24.



miro

Figure 24. System boundaries of different scenarios for cellulose insulation, from the perspective of the 2nd life cycle in which the EoL cellulose insulation is valorised, according to the APOS approach. The dotted arrows indicate physical flows of material/energy, which are “overruled” by a restructuring of processes to establish the partitioned system. Thick solid arrows show the co-products of a joint production process, which are partitioned according to their relative economic revenue.

12.3.4.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

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

Production of SRF: The user of the SRF is partly accountable (defined by the relative economic revenue) for impacts of the production of the cellulose insulation and the formulation of the SRF. The user is furthermore entirely accountable for 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 impacts of the production of the cellulose insulation and the recycling of insulation into the stabilizing agent. Further downstream processes related to the manufacturing of asphalt are entirely modelled by the user.

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

Reuse into insulation: The second user of the cellulose insulation material is partly accountable (defined by the relative economic revenue compared with the first user) for impacts of the production of the cellulose insulation and the preparation for reuse. At the end of life of the second use of the material, 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 among the second user and the third user, based on the relative economic revenue they provide. 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. 2016c) to calculate the average impacts attributable to a single use cycle of the material.

12.3.5 Limitations of Allocation at the Point of Substitution

The following limitations have been observed regarding APOS:

- Although APOS provides a purely attributional LCA perspective, no industrial standard has adopted APOS as 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.
- 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.
- 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.
- The definition of “end of life” is still open for interpretation. For example, in the case of reuse, the end of life may be after a first use, or after all potential uses. A definition needs to be found within the LCA

community that allows for a consistent application of APOS across uses in this situation.

- 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 modelling.

12.3.6 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by APOS, the following circularity strategies may result in a beneficial effect of the product assessment using APOS:

- Increase recycled content
- Increase EoL recycling rate
- Increase EoL energy recover rate
- Minimize quality degradation
- Use recycled materials with low economic value/low demand
- Produce recycled materials with high economic value/high demand
- Produce recovered energy with high economic value/high demand
- Use recovered energy with low economic value/low demand
- Increase reuse
- Decrease impacts of the recycling process of the recycled content
- Decrease impacts of the recycling process at the end of life
- Decrease impacts of primary raw material production
- Decrease impacts of the energy recovery process
- Decrease impacts of waste disposal
- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Enable the use of a material in multiple loops in cascades
- Increase the efficiency of the recycling process at the EoL
- Increase the fraction of an EoL material that is collected for composting
- Increase the efficiency of the recycling process for the recycled content
- Increase the fraction of biological materials used which originate from Sustained Production
- Increase the fraction of a material collected for recycling at EoL
- Increase the fraction of a material collected for component reuse
- Increase the average number of uses of a material
- Increase the number of different users of a product during its use phase (via sharing/leasing)
- Decrease the mass of unrecoverable waste going to landfilling
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Increase the share of reused content in a product
- Increase the share of renewable content in a product
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use
- Increase the refurbishing rate
- Increase the remanufacturing rate

However, other circularity strategies may not result in noticeable benefits while applying APOS, as this method does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 19 can be used to provide this complementary information.

Table 19. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by APOS.

Circularity strategies not covered by the methodology	Comparative LCA using APOS	PEF Guide	EN 15804	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Increase the functional characteristics of the produced recycled material at the end of life	Yes	Yes	Yes	Yes	Yes			
Increase impacts of substituted primary raw material production	Yes	Yes	Yes	Yes			Yes	
Avoid primary energy sources with high environmental impacts	Yes	Yes	Yes	Yes				
Increase the lifetime of a product	Yes					Yes	Yes	Yes, optionally
Avoid waste treatment with high environmental impacts	Yes			Yes				
Avoid other valorisation processes with high environmental impacts	Yes			Yes				
Decrease impacts of downstream effects due to the substitution of a primary material				Yes	Yes			
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery						Yes	Yes	
Maximize the recovery potential up to theoretical limits							Yes	Yes
Use less critical raw materials							Yes	
Increase the revenue generated relative to the total mass of linear resource inflows							Yes	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP								Yes, optionally

12.4 Consequential LCA

12.4.1 Introduction to the methodology

Consequential LCA is an LCA approach that aims to assess the effects of a change, also referred to as the effects of a decision, which is often expressed as the increase or decrease in demand of a certain 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 impacts of processes that are *affected* by the studied change. Consequential LCA is not a standardized method. There are different interpretations on how to conduct a consequential LCA, for example by including/excluding rebound effects, or by applying economic models (e.g. partial/general equilibrium models). In this report, the approach for consequential LCA is based on (Weidema 2003; Weidema et al. 2009), which is also implemented into the consequential system model of ecoinvent V3 (Weidema et al. 2013). Often, the assumption is done that, besides the assessed change of the functional unit, the demand for other products in the market remains the same (*ceteris paribus*). Relevant aspects of a consequential LCA are therefore:

- **Constrained/unconstrained suppliers:** unconstrained suppliers are suppliers of a product that can easily increase or decrease the production volume of a product. Constrained suppliers cannot change the production volume, even if the demand for a product changes. An example of a constrained supplier is the supplier of a by-product, as the production volume of the by-product is determined by the demand for the main product of the production process. The supply of recycled materials or recovered energy is also constrained, as it is dependent on the production volume of the primary raw materials that are valorised at the end of life.
- **Time-frame of assessment of the effects of a decision:** In the short term, more suppliers are constrained than in the long term, as supply is limited by the installed production capacity. If demand shows a consistent increase over time, the installed capacity can be expanded to fulfil this increased demand. Also, a decrease in demand may not instantaneously lead to a decrease in production, but it may give a signal that less investment is required in the increase of production capacity. In practice, CLCA studies often consider the effects of a decision in the long term, considering changes in production capacity.
- **Size of the change:** The size of the change influences the type of processes that are affected by the change. If the change is small, i.e. not influencing the entire market, the size of the change can be expressed as "marginal". The functional unit can be formulated in terms of "1 product". However, if the size of the change is likely to change the structure of the market, such as a political decision to stop the production of combustion-type cars in 2030, the change is considered as "significant" (Ekvall et al. 2016). The functional unit should then represent the total quantity of products affected by the decision (e.g. production of 10 million electric vehicles).
- **Marginal supplier:** If a product can be supplied by multiple types of suppliers, or by different technologies, only the *marginal* supplier is affected by a change in demand for a product. The marginal supplier is the supplier that is most likely to increase or decrease its production volume. In markets with a stable or growing demand, the marginal supplier is often a modern, competitive technology (Weidema et al. 2009). If the studied decision is a significant change in the market, the average mix of technologies is likely to be affected (Ekvall et al. 2016).
- **Marginal user:** When the supply of a product is constrained, which is the case for by-products and recycled materials, the additional demand does not lead to an increase in production. Instead, it could affect the use of the product by other users. The user that is most likely to stop using a product (e.g. when it becomes more expensive) and use a substitute instead, is called the "marginal user". The substitute product may be a different type of product, providing the same functionality.

Figure 25 is applicable to recycling situations when a recycled/recovered product is bought on a generic market, and when, at the end of life, a waste material is sold to the market for further treatment.

According to the diagram, when the demand for the functional unit results in the additional demand for a recycled or recovered product (of which supply is inherently constrained), it must be determined whether the demand for this recycled product is constrained or not; in other words, whether there is a surplus of this recycled material, or rather a shortage. If demand is constrained (indicated by a parameter value of $A = 0$), the demand for a recycled material results in increased valorisation, and decreased waste treatment. If demand is unconstrained ($A = 1$), the additional demand results in a decreased use of this recycled material by the marginal user, and the increased demand for an alternative (e.g. primary) product by this marginal user. Indirect effects experienced by this marginal user, related to this substitution, must be modelled as well.

The effects of an additional supply of a recyclable waste at the end of life are modelled by the increased supply of a dependent intermediate flow. Also here, if there is a lack of demand for this flow ($A = 0$), the supply of this flow results in the additional waste treatment, modelled by the marginal treatment process (i.e. the process that is most likely to be increasingly used to treat the flow). If there is sufficient demand for this flow for valorisation ($A = 1$), the marginal valorisation process is modelled, and it is considered that the valorised output is used by the marginal user, that decreases its demand for an alternative product. Also here, indirect effects related to the substitution are considered.

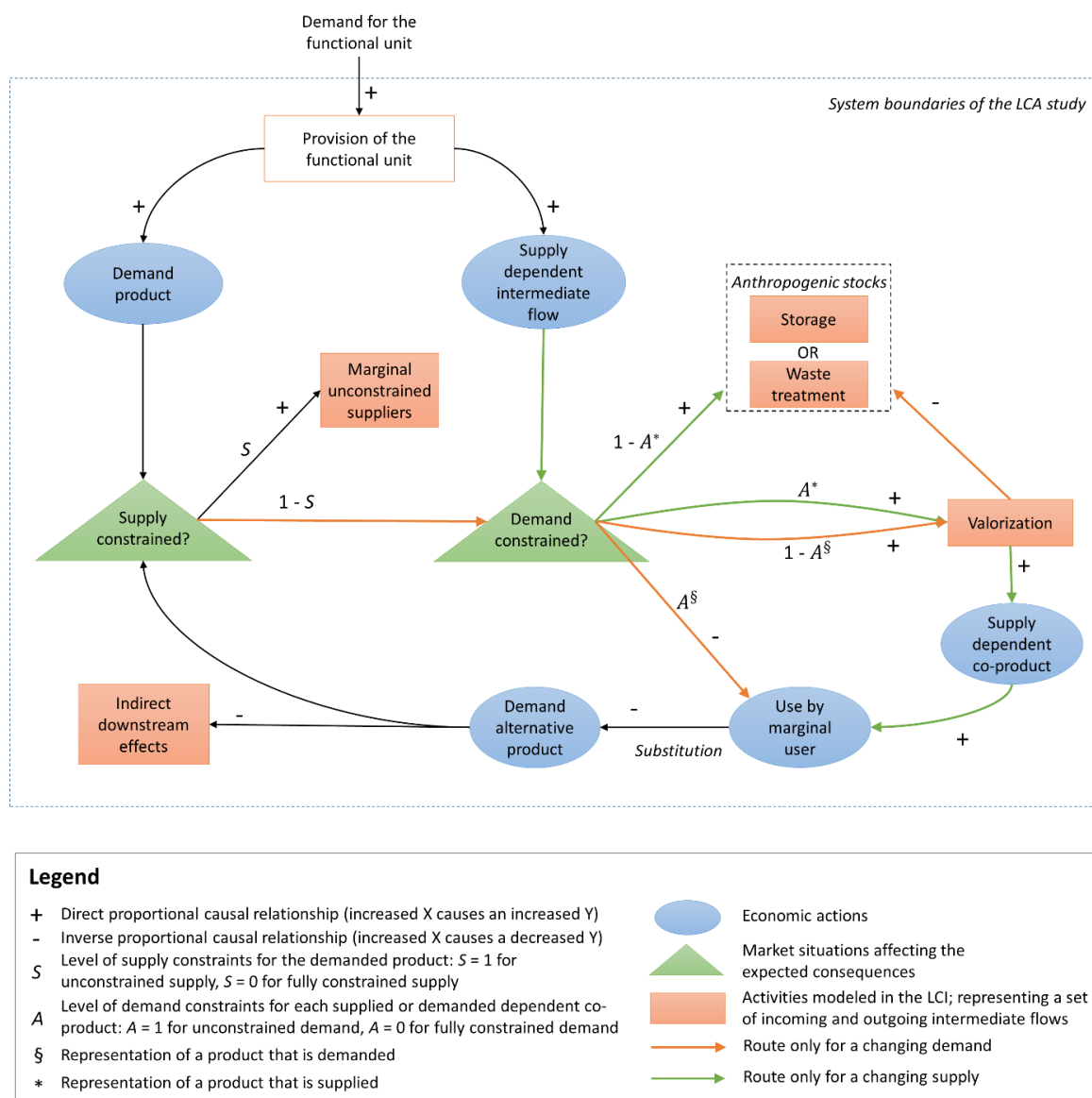


Figure 25. Causal Loop Diagram showing the market-driven consequences of a changing demand for the functional unit. The processes affected by the changing demand for a product and the changing supply of a dependent intermediate flow (e.g. a waste) are modelled in the background subsystem (Schrijvers et al. 2021b)

(Schrijvers et al. 2021b) propose a modified diagram for the scenarios in which the waste valorisation process takes place within the foreground subsystem. In that case, the manufacturer of a product valorises the waste itself, or has contractual agreements with a waste valoriser. Also, at the end of life, the waste may be sent to a specific valorisation facility. In that case, waste valorisation is not determined by market interactions but controlled by value-chain actors. Then, it is not the consumed recycled material that is bought from the market, but rather the to-be-valorised waste. At the end of life, it may not be the waste that is put on the market, but rather the valorised product. If waste valorisation is modelled within the foreground subsystem, Figure 26, which is a modified version of

Figure 25, is used to assess the consequences of waste valorisation.

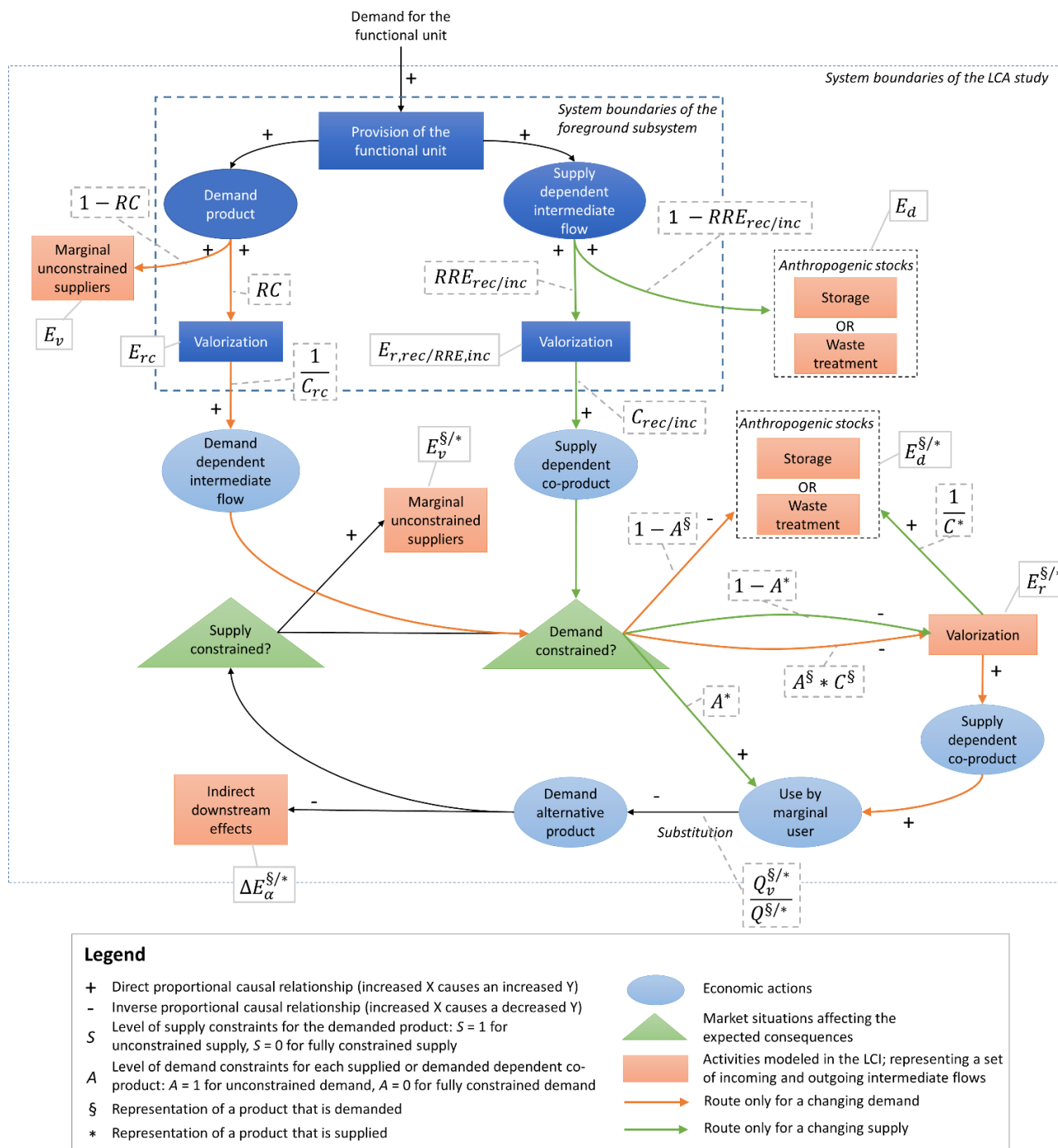


Figure 26. Causal Loop Diagram with the valorisation of the recycled content and the recycled material at the end of life within the boundaries of the foreground subsystem. Processes that are part of the foreground subsystem are indicated by a dark blue colour. Labelled boxes and arrows are terms used in the market-driven substitution method, cf Table 20. RC = recycled content, RRE = end-of-life recycling rate, A = demand constraints, C = conversion efficiency, Q_v/Q = quantity of alternative product displaced per quantity of product under study, E_v = inputs and outputs caused by primary production, E_r = inputs and outputs caused by valorisation (e.g. recycling or recovery), E_d = inputs and outputs caused by waste treatment or stockpiling, ΔE_a = inputs and outputs caused by downstream effects. A more detailed description of the terms is provided in Table 20 (Schrijvers et al. 2021b).

Figure 26 provides labels for flows and processes, which are captured in a mathematical formula – the “market-driven substitution method” – in the style of the Circular Footprint Formula of the PEF Guide to capture the modelling of a life cycle which uses a recycled material, and which recovers material/energy at the end of life. The parameters of this set of formulas are explained in Table 20.

$$\begin{aligned}
 \text{E1. } E_{tot} &= E_{tot,material} + E_{tot,energy} + E_{tot,disposal} \\
 \text{E2. } E_{tot,material} &= (1 - RC) * E_v + RC * \left(E_{rc} - \frac{1-A^S}{C_{rc}} * E_d^S - \frac{A^S * C^S}{C_{rc}} * \left(E_r^S + \frac{Q_v^S}{Q^S} * (\Delta E_\alpha^S - E_v^S) \right) \right) + \\
 &\quad RRE_{rec} * C_{rec} * \left(E_{r,rec} - (1 - A^*) * \left(E_r^* - \frac{E_d^*}{C^*} \right) + A^* * \frac{Q_v^*}{Q^*} * (\Delta E_\alpha^* - E_v^*) \right) \\
 \text{E3. } E_{tot,energy} &= RRE_{inc} * (E_{RRE,inc} - C_{inc} * E_v^*) \\
 \text{E4. } E_{tot,disposal} &= (1 - RRE_{inc} - RRE_{rec}) * E_d
 \end{aligned}$$

Technically, the production/use of recovered energy can be followed by the same formula as the production/use of recovered materials. To show the resemblance with the CFF of the PEF Guide, some simplifying assumptions have been made to the consequential approach to obtain this formula (Schrijvers et al. 2021b):

- Demand for recovered electricity and heat are unconstrained ($A = 1$)
- No indirect effects take place by using recovered energy instead of energy from conventional sources
- Recovered energy substitutes energy from conventional sources with a 1:1 quantity ratio.

For a more detailed assessment, it is preferable to model all inputs and outputs (including recovered energy and recovered materials) via the diagrams of

Figure 25 (if valorisation is modelled in the background system), or Figure 26 (if valorisation is modelled in the foreground system).

Table 20. Parameters of the market-driven substitution method and their explanation (Schrijvers et al. 2021b)

Parameter	Explanation	Value
E_{tot}	Inputs and outputs caused by the demand for the function under study via a consequential LCA	Inputs and outputs / unit of analysis
E_v	Inputs and outputs caused by the extraction and processing of primary (virgin) materials via the marginal production process (including processing inefficiencies)	Inputs and outputs / unit of primary material
E_v^S	Inputs and outputs caused by the extraction and processing of primary (virgin) materials that are substituted by the marginal user of the demanded recycled material (including processing inefficiencies)	Inputs and outputs / unit of primary material
E_v^*	Inputs and outputs caused by the extraction and processing of the primary (virgin) materials that are substituted by the marginal user of the supplied material (including processing inefficiencies)	Inputs and outputs / unit of primary material
E_{rc}	Inputs and outputs caused by the production of the demanded recycled material (including collection and recycling inefficiencies)	Inputs and outputs / unit of produced recycled material
$E_{r,rec}$	Inputs and outputs caused by the production of the supplied recycled material (including collection and recycling inefficiencies)	Inputs and outputs / unit of produced recycled material

$E_r^{\S}$	Inputs and outputs caused by the production of the demanded recycled material via the marginal valorisation process (including collection and recycling inefficiencies)	Inputs and outputs / unit of produced recycled material
E_r^*	Inputs and outputs caused by the production of the supplied recycled material via the marginal valorisation process (including collection and recycling inefficiencies)	Inputs and outputs / unit of produced recycled material
$E_{RRE,inc}$	Inputs and outputs caused by the incineration of the end-of-life product (including collection and processing inefficiencies)	Inputs and outputs / unit of incinerated end-of-life product
E_d	Inputs and outputs caused by waste treatment or storage	Inputs and outputs / unit of discarded or stored material
$E_d^{\S}$	Inputs and outputs caused by the waste treatment or storage of the demanded recycled product via the marginal treatment process	Inputs and outputs / unit of discarded or stored material
E_d^*	Inputs and outputs caused by the waste treatment or storage of the supplied recycled product via the marginal treatment process	Inputs and outputs / unit of discarded or stored material
$\frac{Q_v^{\S}}{Q^{\S}}$	Quantity-correction factor that indicates the amount of a primary material that the marginal user substitutes by the demanded recycled material	Unit of substituted primary material / unit of recycled material
$\frac{Q_v^*}{Q^*}$	Quantity-correction factor that indicates the amount of a primary material that the marginal user substitutes by the supplied recycled material	Unit of substituted primary material / unit of recycled material
$\Delta E_{\alpha}^{\S}$	Inputs and outputs due to additional (+) and/or decreased (-) downstream intermediate or elementary flows related to the distribution, use, and disposal of the recycled material instead of a primary material by the marginal user of the demanded recycled material	Inputs and outputs / unit of substituted primary material
ΔE_{α}^*	Inputs and outputs due to additional (+) and/or decreased (-) downstream intermediate or elementary flows related to the distribution, use, and disposal of the recycled material instead of a primary material by the marginal user of the supplied recycled material	Inputs and outputs / unit of substituted primary material
RC	Recycled content (recycled or recovered material input per unit of analysis)	$0 \leq RC \leq 1$
RRE_{rec}	End-of-life recycling rate (share of the product at the end of life that is sent to recycling)	$0 \leq RRE_{rec} \leq 1$
RRE_{inc}	End-of-life incineration rate (share of the product at the end of life that is sent to incineration)	$0 \leq RRE_{inc} \leq 1$
C_{rc}	Conversion efficiency of the recycling process of the demanded recycled material	Unit of useful output / unit of input material
C_{rec}	Conversion efficiency of the recycling process of the supplied material	Unit of useful output / unit of input material
C_{inc}	Conversion efficiency of the energy recovery process of the supplied material	Unit of useful output / unit of input material
$C^{\S}$	Conversion efficiency of the marginal valorisation process of the demanded recycled material	Unit of useful output / unit of input material

C^*	Conversion efficiency of the marginal valorisation process of the supplied recycled material	Unit of useful output / unit of input material
A^S	Indicator for demand constraints of the used recycled material ($A^S = 0$ reflects fully constrained demand; $A^S=1$ reflects fully unconstrained demand)	$0 \leq A^S \leq 1$
A^*	Indicator for demand constraints of the supplied recycled material ($A^* = 0$ reflects fully constrained demand; $A^*=1$ reflects fully unconstrained demand)	$0 \leq A^* \leq 1$

12.4.2 Circularity challenges and data needs

Table 21. Addressing of circularity challenges by the market-driven substitution method.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	The market-driven substitution method does not address time-differentiated emissions of GHGs. The same adaptations of the LCI may be made in a consequential LCA as in an attributional LCA, that favours or discounts the effect of delayed emissions.
Allocation of biogenic carbon and carbon storing capability	In CLCA, the benefits of the use of biogenic carbon or carbon storage are only addressed if the decision under study (i.e. the functional unit) results in a <i>net</i> decreased emission or absorption of GHGs, across multiple life cycles. Carbon capture is modelled in the process that absorbs GHGs, and emissions in the process that emits them, even if this process takes place in another product's life cycle. Differences between bio-based and fossil-based products (such as differences in recyclability) are accounted for in "indirect downstream effects", resulting that only the <i>net</i> difference in GHG emissions between the decision scenario and an alternative scenario result in the consideration of benefits of carbon storing. These benefits are allocated to the stakeholders involved in the implementation of the decision.
Addressing the longevity of products	Depending on whether there is a demand for a product that is available for reuse at the end of life, benefits of substituting an alternative product are either attributed to the actor that makes the product available for reuse (in the case of high demand) or to the actor that reuses the product (in case of low demand). If a product is made available that can be reused in multiple life cycles, all subsequent occasions of reuse could be considered as "indirect effects", modelled by the actor that makes the product first available.
Multiple loops, finite loops, steady/non-steady state	For a recycled material that is consumed, multiple historical loops are irrelevant. The only question is whether there is a high or a low demand for this recycled material. Based on this determination, either the decreased use of this material in other product systems, or decreased waste treatment, are modelled, respectively. For recycled materials made available at the end of life, projections need to be made on the behaviour of the marginal user; whether the

	material is likely to be recycled at the end of the second life. Here, assumptions made on the future recyclability of a material result in increased uncertainty associated with the LCI. This can be resolved by comparing a conservative scenario with an optimistic scenario, or by limiting the system boundaries to effects taking place in a defined time frame, arguing that the modelling of additional effects does not provide a reliable view on the effects of the decision.
Cascading chains	Historical cascading chains are out of scope of the assessments (as they are not affected by a current decision). Future cascading chains can be modelled as “indirect effects” of making a recycled material available for further use (as long as these effects are different than what is to be expected for the substituted product in the market). Differences in quality with a substituted material are considered by modelling differences in downstream processes, such as manufacturing, transport, use, and subsequent recyclability.

12.4.3 Supplier of recovered material/energy at end of life

12.4.3.1 *Research questions*

From the perspective of the supplier of a recycled or recovered material/energy flow, the following research questions can be addressed by the application of a consequential LCA:

- What environmental impacts are caused by the additional demand for a product that is recyclable/recoverable at the end of life?
- Should I make (part of) my product recyclable/recoverable at the end of life to decrease environmental impacts?

Other variations on these questions may be formulated as well. These questions may be asked by actors that are involved solely in the first life cycle of the product, such as the manufacturer of the product, or the user of the product. In comparison to other research questions, these questions focus on a *change* (e.g. the additional demand for a product or applying a different end-of-life scenario).

12.4.3.2 *Functional unit*

As mentioned above, the size of the functional unit ideally represents the size of the change. If the change is made on a company or consumer scale (a small change in production volume), the functional unit could represent the additional supply of or demand for a single unit of a product. However, if the change affects the entire market (a significant change in production volume), the size of the functional unit should represent the total quantity of the change.

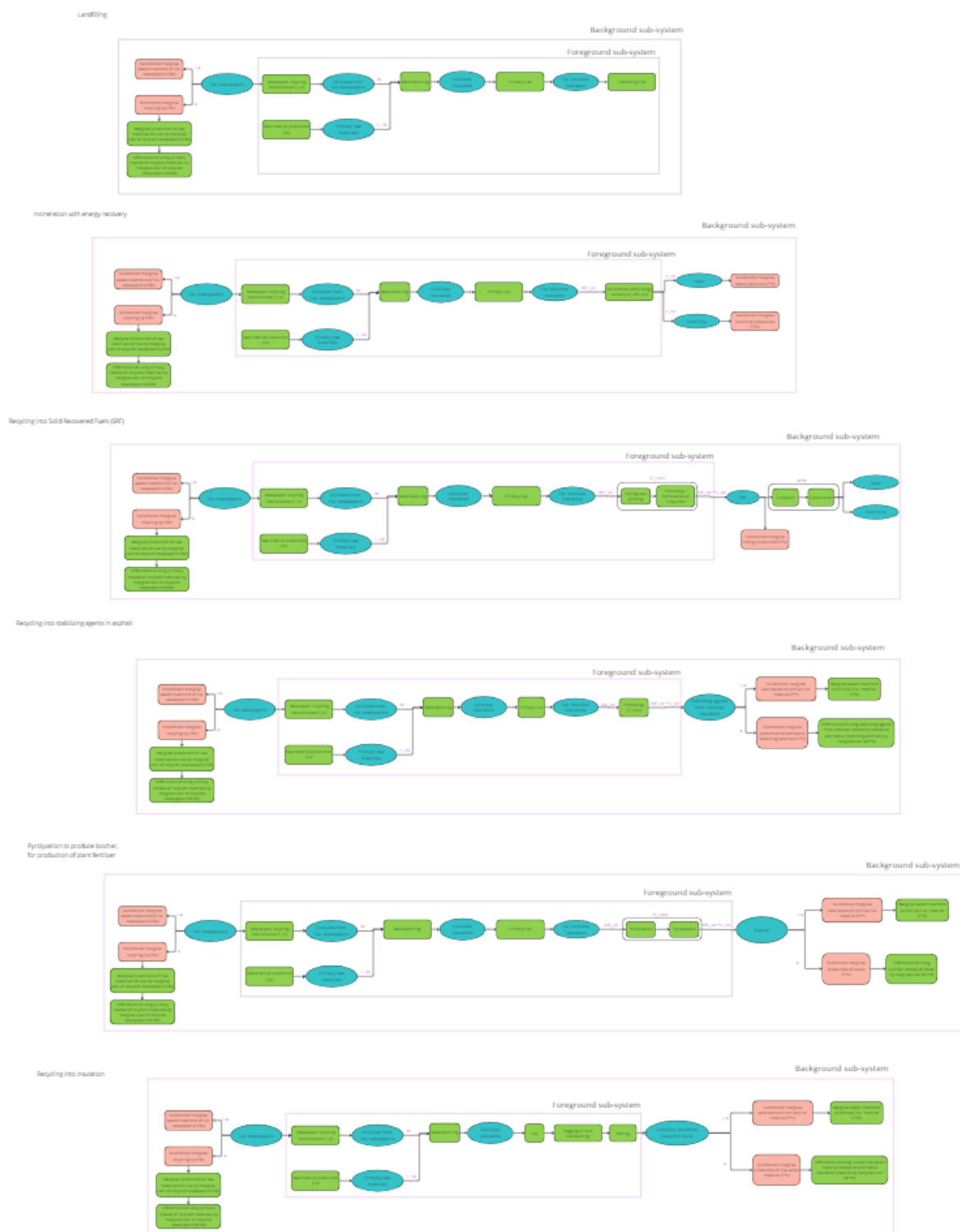
- Small change in production volume: Cellulose-based insulation material for the thermal insulation of 100 m², providing a thermal resistance of 5 m².K/W, for the duration of 50 years.
- Significant change in production volume: Cellulose-based insulation material for the thermal insulation of all houses in a certain country, providing a thermal resistance of 5 m².K/W, for the duration of 50 years.

In order to clarify that the study assesses the environmental impacts of a change, the following wording can be added to the functional unit:

- The additional production of...
- The additional installation of...
- The additional use of ...
- The additional demand for ...

12.4.3.3 System boundaries

The system boundaries of the first life cycle of the illustrative example, in which the EoL cellulose insulation is valorised, are shown for the different scenarios in Figure 27.



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Figure 27. System boundaries of different scenarios for cellulose insulation, from the perspective of the 1st life cycle in which the EoL cellulose insulation is valorised, according to the presented Consequential LCA approach.

12.4.3.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

All scenarios: One of the raw material inputs is cellulose from end-of-life newspapers, indicated as the “recycled content” of the insulation material. As the recycled flow 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 that this flow is taken from the generic market. This flow is modelled as “increased demand dependent intermediate flow” in Figure 26. 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 a 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 considered as an average over different geological locations (Schrijvers et al. 2021b). For illustrative purposes, a value of $A = 0.3$ is applied here. This means that the use of EoL newspapers as an input in the cellulose recycling process results for 70% in the substitution of the marginal waste treatment of these EoL newspapers, such as the substitution of 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 that this flow is recycled by the marginal valorisation process of EoL newspapers. This recycling process could be, for example, the closed-loop recycling into newspapers. The marginal user of recycled newspapers now must find another raw material source, such as primary pulp for the production of 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 modelled as indirect downstream effects. As a result of using a 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: System boundaries are shown in correspondence with the market-driven substitution formula, which is a simplified interpretation of the cause-and-effect relationships shown in Figure 26. The energy valorisation process is drawn within the foreground subsystem. The incineration process produces heat and electricity, based on the conversion efficiency of the process (parameter “C”). It was assumed in the construction of the formula that demand of 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 are no further differences for the marginal user to use recovered energy or another type of 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 modelled via the diagram of Figure 26. A constrained demand for heat could result in the fact that heat from another source ceases to be valorised, or that more heat is wasted via 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 Figure 26 are followed, which provides a more detailed reflection, although the modelling 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 the production of 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 brought to a specific market, such as cement industries, the substituted marginal energy production is identified specifically to this 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 noticed by the marginal user are differences in the transport of SRF, as well as differences in emissions caused by SRF compared to the use of the alternative energy source (e.g. coal).

Recycling into stabilizing agents in asphalt: Valorisation of the EoL insulation material is modelled as part of the foreground system up to the point that stabilizing agents are sold to the market. The 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 in some areas demand may be well developed, while in other areas there may be a surplus of this type of stabilizing agents. As a consequence, 50% of the supplied stabilizing agents may substitute 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, such as potential leaching of the stabilizer, requirements for maintenance, or differences in treatment at the end of life. The remaining 50% of the supplied stabilizer may result in a decrease in waste valorisation for this purpose in other product systems, which may be other sources of insulation material, or other types of (organic) materials. These wastes are now increasingly treated by their marginal waste treatment process, such as incineration. The affected processes may be identified by market research or by making simplifying assumptions, such as that the affected valorisation processes in the market are similar to the valorisation process in the foreground system.

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

Reuse into insulation: In the case of reuse, the choice of where to put the system boundaries is dependent on the level of control of the reuse chain 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 modelled by the marginal disposal process the background system. The system boundaries of the foreground system may then coincide with the system boundaries in the application of the CFF (Figure 19). However, if reuse is left up to market dynamics, the question is whether the demand for insulation for reuse is saturated or not (as depicted in Figure 27). Reusable insulation material may compete with other types of reuseable insulation material, or insulation material from (other types of) recycled material. Also here, the determination of the marginal valorisation process for insulation material may be based on market research or simplifying assumptions.

12.4.4 User of recovered material/energy

12.4.4.1 *Research questions*

From the perspective of the user of a recycled or recovered material/energy flow, the following research questions can be addressed by the application of a consequential LCA:

- What environmental impacts are caused by the additional demand for a product that contains recycled/recovered material/energy?
- Should I use recycled/recovered material/energy in my product to decrease environmental impacts?

Other variations on these questions may be formulated as well. These questions may be asked by actors that are involved solely in the second life cycle of the product, such as the manufacturer of the product, or the user of the product. Also in this life cycle, these questions focus on a *change* (e.g. the additional demand for a product).

12.4.4.2 *Functional unit*

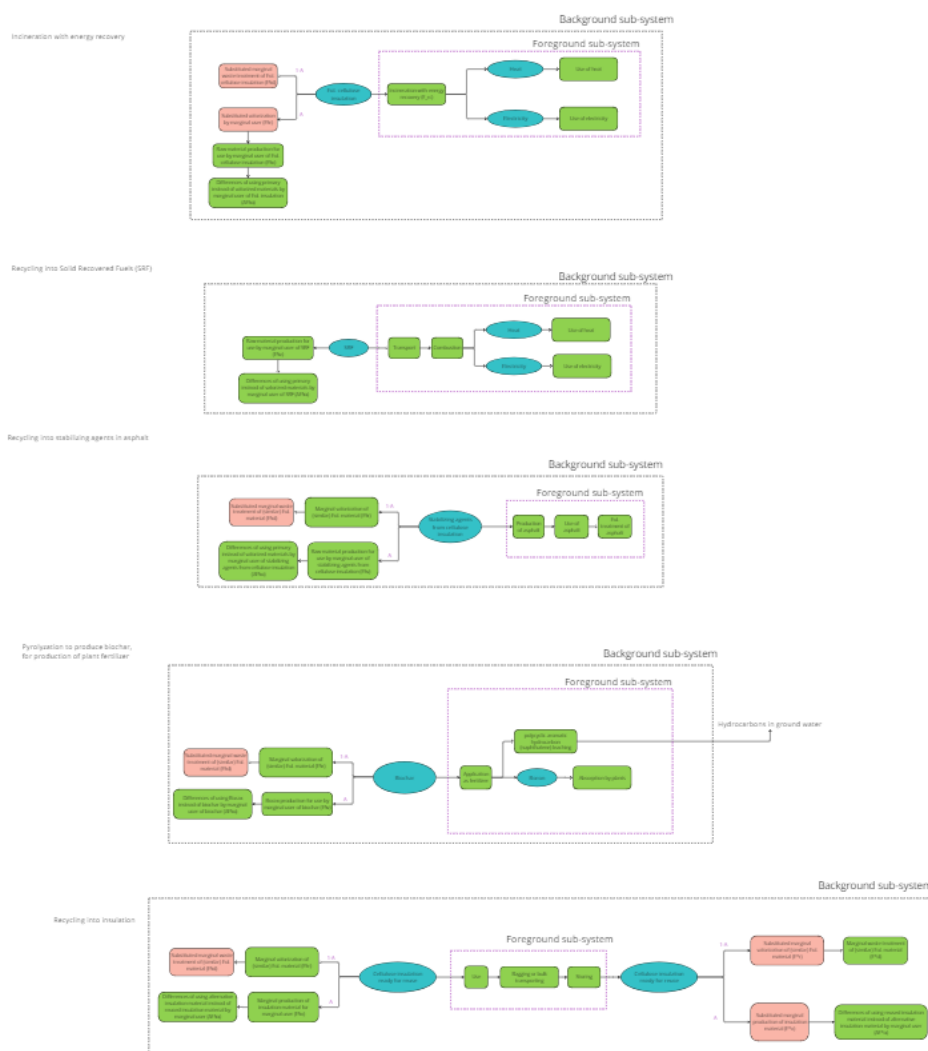
Also here, the functional unit for the user of the secondary raw material or energy is scenario-specific, as the scenarios provide different outputs for a subsequent life cycle. The declared unit or reference flow could therefore be, for example, a certain quantity of energy used, a certain quantity of boron needed for fertilization of plants, or a quantity of asphalt produced.

In order to clarify that the study assesses the environmental impacts of a change, the following wording can be added to the functional unit:

- The additional production of...
- The additional installation of...
- The additional use of ...
- The additional demand for ...

12.4.4.3 *System boundaries*

The system boundaries of the second life cycle of the illustrative example are shown for the different scenarios in Figure 28. It must be noted that the system boundaries may not necessarily coincide with the system boundaries as formulated by the supplier of a valorised material (Figure 27). For example, the user of recovered heat may just purchase “heat” on the market, or this user may specifically choose to purchase recovered heat from a specific incineration facility. In the first case, “heat” would be an incoming flow of the foreground subsystem, whereas in the second case the incineration process is included within the boundaries of the foreground system. The modelled consequences may differ, due to differences in demand constraints of the flows entering the foreground system.



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Figure 28. System boundaries of different scenarios for cellulose insulation, from the perspective of the 2nd life cycle in which the EoL cellulose insulation is valorised, according to the presented Consequential LCA approach.

12.4.4.4 Allocation of circular processes

From the system boundaries, the following observations can be made about the modelling of processes in the different scenarios.

Incineration with energy recovery: If the user of the recovered energy would 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 decreased use of this energy by its marginal user, who will increase its consumption of energy from alternative sources, modelled via the marginal production processes. However, if the user of the recovered energy is in charge of the recovery process itself, it is not the recovered energy but the end-of-life cellulose insulation that it purchases on the market. This is illustrated by the system boundaries in Figure 28. Here, it must be assessed whether the demand for EoL insulation material is constrained or not. 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 modelled 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 valorised by the marginal valorisation process. One could imagine exports to other countries flow low-value valorisation, substituting raw material needs in remote economies. Such information may be provided by market research or LCA databases.

Figure 25, and considering that demand for SRF is unconstrained, the additional use of SRF results in a decreased use of SRF 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 market of cement industries, this marginal production process may be the production of energy from coal. In addition, the user of SRF under study models the emissions related to the use of coal, and subtracts the emissions related to the use of SRF, as observed by this marginal user. In practice, it could mean that the combustion process of SRF in the foreground system is cancelled out by a decreased combustion of SRF in the background system and replaced by emissions related to the use of coal in the background system.

Recycling into stabilizing agents in asphalt: Similar to the scenario of 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 valorised material: $A = 0.5$. This means that the life cycle of the asphalt models for 50% the additional valorisation 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 modelled as a decreased use of this flow 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 the use as fertilizer: Also here, modelling follows the same pattern as 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 modelled for 50% as an increased valorisation of similar EoL materials and substituted marginal waste treatment of these materials. For the remaining 50%, the use of biochar results in a decreased use by the marginal user (assumed to be also the fertilizer application), where instead Borax is now used. This results in an increase in production of Borax, as well as an increase in downstream effects related to the use of Borax (e.g. leaching) minus the effects related to the use of biochar in the background system. This means that the leaching of hydrocarbons in ground water, as modelled in the foreground system, may be cancelled out by an avoided leaching of hydrocarbons in ground water in the background system, and compensated by an increased leaching of Borax in the background system.

Reuse into insulation: System boundaries are drawn here aligned with the system boundaries of the supplying life cycle, 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 modelled by the additional valorisation of similar EoL material and substituted waste treatment, and partly by a decreased 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 another round of reuse, the mirrored effects are modelled at the end of life. This means that, as long as the recycled content is equivalent to the end-of-life recycling rate, it does not make a difference in the environmental impacts whether reuse is organized via the market or within the boundaries of a single company. However, the market situation (the demand constraints) influences the type of effects that are modelled by these exchanges with the market. If demand is low, a focus is put on increased/decreased valorisation in the market, and decreased/increased waste treatment, respectively. However, is demand for the material is

generally high, a focus is put 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 favourable to focus on *using* a 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).

12.4.5 Limitations of Consequential LCA

The following limitations have been observed regarding the presented Consequential LCA approach:

- Data are needed for both foreground processes (processes under control by value-chain actors) and background processes (marginal production, waste treatment, and valorisation 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 process specifically for biobased materials. Data may be used from other sources, but, as most other sources provide attributional data, remodelling must be done to make the data compatible with the consequential model (e.g. modelling 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. However, the A-values as communicated by the European Commission for the application of the Circular Footprint Formula (European Commission 2020) may provide a starting point, as these values have been developed with the purpose to represent the market situation of recycled/recovered materials.

12.4.6 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by the Consequential LCA approach, the following circularity strategies may result in a beneficial effect of the product assessment using CLCA:

- Increase recycled content
- Increase EoL recycling rate
- Increase EoL energy recover rate
- Minimize quality degradation
- Use recycled materials with low economic value/low demand
- Produce recycled materials with high economic value/high demand
- Increase the functional characteristics of the produced recycled material at the end of life
- Produce recovered energy with high economic value/high demand
- Use recovered energy with low economic value/low demand
- Increase reuse
- Decrease impacts of the recycling process of the recycled content
- Decrease impacts of the recycling process at the end of life
- Decrease impacts of primary raw material production
- Increase impacts of substituted primary raw material production
- Decrease impacts of the energy recovery process
- Avoid primary energy sources with high environmental impacts
- Decrease impacts of waste disposal

- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Enable the use of a material in multiple loops in cascades
- Decrease impacts of downstream effects due to the substitution of a primary material
- Increase the efficiency of the recycling process at the EoL
- Increase the fraction of an EoL material that is collected for composting
- Increase the efficiency of the recycling process for the recycled content
- Increase the fraction of biological materials used which originate from Sustained Production
- Increase the fraction of a material collected for recycling at EoL
- Increase the fraction of a material collected for component reuse
- Increase the average number of uses of a material
- Increase the number of different users of a product during its use phase (via sharing/leasing)
- Decrease the mass of unrecoverable waste going to landfilling
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Increase the share of reused content in a product
- Increase the share of renewable content in a product
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use
- Increase the refurbishing rate
- Increase the remanufacturing rate
- Avoid waste treatment with high environmental impacts
- Avoid other valorisation processes with high environmental impacts

However, other circularity strategies may not result in noticeable benefits while applying CLCA, as this method does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 22 can be used to provide this complementary information.

Table 22. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by Consequential LCA.

Circularity strategies not covered by the methodology	Comparative LCA using CLCA	MCI	CTI	ISO 59020:2024
Increase the lifetime of a product	Yes	Yes	Yes	Yes, optionally
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery		Yes	Yes	
Maximize the recovery potential up to theoretical limits			Yes	Yes
Use less critical raw materials			Yes	
Increase the revenue generated relative to the total mass of linear resource inflows			Yes	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP				Yes, optionally

12.5 Process-oriented LCA from the recycler/valorizer perspective

Whether a waste should be valorised to generate environmental benefits (e.g. compared to the non-valorisation of the waste) does not necessarily require a product-perspective (or life-cycle perspective) as applied in the sections that focus on the first and the second life cycle associated with the valorisation process. Instead, a process-oriented perspective could be applied (as introduced by (Schrijvers et al. 2020)), that focuses on the processes that are affected by the implementation of a valorisation process.

12.5.1 Circularity challenges and data needs

Table 23. Addressing of circularity challenges by system expansion in a process-oriented LCA.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	Not addressed
Allocation of biogenic carbon and carbon storing capability	Not addressed
Addressing the longevity of products	Outside scope of assessment
Multiple loops, finite loops, steady/non-steady state	Outside scope of assessment
Cascading chains	A single occasion of open-loop recycling may be represented, by formulating the specific input waste and the output of recovered material/energy, which may be applicable in a cascade. If the entire cascade is to be modelled, guidance of Section 12.6 may be applied.

12.5.2 Application to the recycling/valorisation process

12.5.2.1 *Research questions*

A process-oriented perspective could serve the following research questions:

- Attributional perspective:
 - o For what environmental impacts is valorisation of an EoL material accountable?
 - o Should a material be valorised, to generate a lower accountability for impacts for the value-chain actors?
- Consequential perspective:
 - o What environmental impacts are caused by the valorisation of EoL material?
 - o Should a material be valorised, to cause lower environmental impacts?

These questions may be asked by actors that are involved in the implementation of the valorisation process, such as recycling actors, collectors, or sorting companies. Also, investors may be concerned, as well as public actors that wish to stimulate waste valorisation to decrease environmental impacts.

12.5.2.2 Functional unit

A waste valorisation process provides a function to two different life cycles: the supplier of the waste (the first life cycle) and the user of the valorised material or energy (the second life cycle). To avoid having to allocate impacts of the valorisation process to either life cycle, the functional unit could comprise both functionalities.

The functionality of the valorisation process can be expressed by the quantity of waste processed to produce a certain quantity of recovered material/energy (Schrijvers et al. 2020). Examples (using fictional quantities):

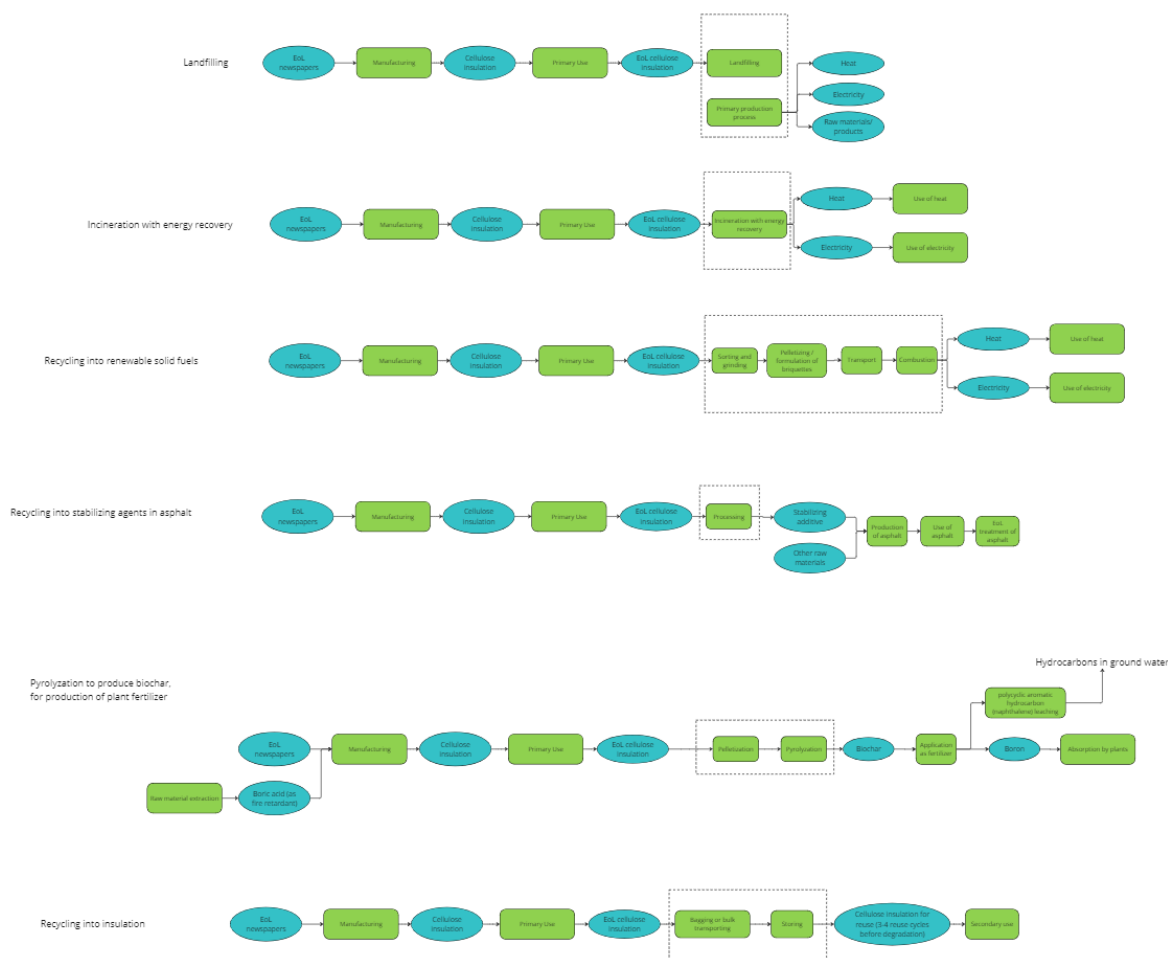
- **Incineration/production of SRF:** Treatment of 10 kg of end-of-life cellulose insulation and production of 5 MJ of electricity and 3 MJ of heat / 5 kg of SRF.
- **Recycling into stabilizing agents in asphalt:** Treatment of 10 kg of end-of-life cellulose insulation and production of 3 kg of stabilizing additive
- **Recycling into biochar for the use as fertilizer:** Treatment of 10 kg of end-of-life cellulose insulation and production of 2 kg of biochar
- **Reuse into insulation:** Treatment of 10 kg of end-of-life cellulose insulation and production of 9 kg of reusable cellulose insulation

12.5.2.3 System boundaries

The system boundaries of an LCA study from the perspective of the recycler, for the different EoL scenarios of cellulose insulation, are shown in Figure 29. In line with the functional unit, the system boundaries show a flow of incoming waste, and an outgoing product (energy or material). The inputs are not “burden-free”, but the *subject* of the analysis. In a comparative LCA, where for example two scenarios are compared with one another, the sizes of the incoming and outgoing functional flows must be equivalent.

If a scenario does not provide 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 would be compared to incineration with energy recovery, for example, an additional energy production process may be added to the landfilling scenario, as illustrated in Figure 29.

If there are upstream or downstream differences among the two scenarios, beyond the boundaries of the recycling or valorisation processes, ideally the system boundaries are extended to include the life cycle stages in which such differences appear. For example, in the example of the production of biochar, if this scenario is compared to the case in which Borax would be used as a fertilizer, ideally the use phase is added to the system boundaries to take the different emissions from leachates into account.



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Figure 29. System boundaries of different scenarios for cellulose insulation, from the perspective of the recycler.

12.5.2.4 Allocation of circular processes

By applying system expansion, there is no need for allocation of impacts or benefits of the circular processes among the different life cycles. The approach is applicable to both attributional and consequential LCA. As the functional flows are not characterized themselves, no market assessment is required for those. Intermediate flows that are assessed are the inputs and outputs of the valorisation process, which may be modelled via an attributional or consequential background database.

12.5.3 Limitations of the Recycler/valorizer perspective

The following limitations have been observed regarding the system expansion applied to the recycler/valorizer perspective:

- The scope is limited to the processes that are included in the recycling/valorisation 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.

12.5.4 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by system expansion from the recycler/valorizer perspective, the following circularity strategies may result in a beneficial effect of the product assessment using this approach:

- Decrease impacts of the recycling process of the recycled content
- Decrease impacts of the recycling process at the end of life
- Decrease impacts of the energy recovery process
- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Increase the efficiency of the recycling process at the EoL
- Increase the efficiency of the recycling process for the recycled content
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use

However, other circularity strategies may not result in noticeable benefits while applying system expansion with a focus on the recycler/valorizer, as this method does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 24 can be used to provide this complementary information.

Table 24. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by System expansion applying the recycler/valorizer perspective.

Circularity strategies not covered by the methodology	Comparative LCA using System expansion – Recycling perspective	PEF Guide	EN 15804	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Minimize quality degradation	Yes	Yes	Yes	Yes	Yes	Yes			Yes
Increase the functional characteristics of the produced recycled material at the end of life	Yes	Yes	Yes		Yes	Yes			Yes
Decrease impacts of primary raw material production	Yes	Yes	Yes	Yes	Yes	Yes		Yes	
Increase impacts of substituted primary raw material production	Yes	Yes	Yes		Yes			Yes	
Avoid primary energy sources with high environmental impacts	Yes	Yes	Yes		Yes				
Decrease impacts of waste disposal	Yes	Yes	Yes	Yes	Yes	Yes			
Avoid waste treatment with high environmental impacts	Yes				Yes				
Avoid other valorisation processes with high environmental impacts	Yes				Yes				
Increase recycled content		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increase EoL recycling rate		Yes	Yes	Yes	Yes	Yes		Yes	Yes

Circularity strategies not covered by the methodology	Comparative LCA using System expansion – Recycling perspective	PEF Guide	EN 15804	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Increase EoL energy recover rate		Yes	Yes	Yes	Yes	Yes		Yes	Yes
Use recycled materials with low economic value/low demand		Yes		Yes	Yes				
Produce recycled materials with high economic value/high demand		Yes		Yes	Yes				
Produce recovered energy with high economic value/high demand		Yes		Yes	Yes				
Use recovered energy with low economic value/low demand				Yes	Yes				
Increase reuse		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Enable the use of a material in multiple loops in cascades				Yes	Yes	Yes		Yes	
Decrease impacts of downstream effects due to the substitution of a primary material					Yes	Yes			
Increase the fraction of an EoL material that is collected for composting		Yes	Yes	Yes	Yes	Yes	Yes		
Increase the lifetime of a product							Yes	Yes, optionally	Yes, optionally

Circularity strategies not covered by the methodology	Comparative LCA using System expansion – Recycling perspective	PEF Guide	EN 15804	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Increase the fraction of biological materials used which originate from Sustained Production		Yes	Yes	Yes	Yes	Yes	Yes		
Increase the fraction of a material collected for recycling at EoL		Yes	Yes	Yes	Yes	Yes	Yes		
Increase the fraction of a material collected for component reuse		Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery							Yes	Yes	
Increase the average number of uses of a material		Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Increase the number of different users of a product during its use phase (via sharing/leasing)		Yes	Yes	Yes	Yes	Yes	Yes		
Decrease the mass of unrecoverable waste going to landfilling		Yes	Yes	Yes	Yes	Yes	Yes		
Increase the share of reused content in a product		Yes	Yes	Yes	Yes	Yes		Yes	Yes

Circularity strategies not covered by the methodology	Comparative LCA using System expansion – Recycling perspective	PEF Guide	EN 15804	APOS	CLCA	System expansion – Multiple life cycles	MCI	CTI	ISO 59020:2024
Maximize the recovery potential up to theoretical limits								Yes, optionally	Yes
Increase the share of renewable content in a product		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Use less critical raw materials								Yes, optionally	
Increase the refurbishing rate		Yes	Yes	Yes	Yes	Yes		Yes	
Increase the remanufacturing rate		Yes	Yes	Yes	Yes	Yes		Yes	
Increase the revenue generated relative to the total mass of linear resource inflows								Yes, optionally	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP									Yes, optionally

12.6 A multi-life cycle approach

Most of the above methods to assess the environmental impacts related to a circularity strategy apply the focus to a product (e.g. 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 by the application of system expansion. System expansion may be applied on a process-level, where the 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 the multiple life cycles that are affected by the implementation of a circularity strategy. This is the ideal approach to identify the environmental benefits of circularity, as a full overview of all effects of the circularity strategy in each subsequent life cycle is provided, and no choices about an allocation procedure need to be made.

12.6.1 Circularity challenges and data needs

Table 25. Addressing of circularity challenges by system expansion in a multi-life cycle LCA approach.

Challenges	How addressed by method
Time-differentiated impacts (dynamic carbon footprinting)	The different timing of carbon emissions may be modelled similar to a product with a long lifetime. Indeed, if multiple loops are included within the system boundaries, the final disposal of a raw material may be after a few decades. The uncertainty of modelling processes in the far future must be well acknowledged.
Allocation of biogenic carbon and carbon storing capability	As the uptake and emissions of biogenic carbon are both considered within the system boundaries, no allocation is necessary.
Addressing the longevity of products	The longevity of products is easily modelled by this approach, as no distinction between modelling of reuse, repair, or recycling need to be considered. The total functionality provided by the product over multiple cycles is the subject of analysis.
Multiple loops, finite loops, steady/non-steady state	Multiple loops can be modelled within the system boundaries. Exploring different scenarios may be valuable in comparing different types of loops, e.g. with different assumptions about quality conservation and open or closed-loop recycling.
Cascading chains	Cascading chains can be modelled within the system boundaries, even if the chains continue beyond the adjacent life cycle of one product.

12.6.2 Application to multiple life cycles

12.6.2.1 Research questions

Examples of research questions that would require a multi-life cycle assessment approach are:

- For what environmental impacts is the cascading use of a raw material that can be used in multiple life cycles accountable? (e.g. attributional LCA assessing the footprint of a single scenario)
- Should I produce a bio-based raw material, considering it can be used in multiple consecutive life cycles, to make the users of the raw material less accountable for impacts? (e.g. comparative attributional LCA)
- What environmental impacts are generated by the (cascading) use of a raw material in multiple life

- cycles? (e.g. consequential LCA assessing the footprint of a single scenario)
- Should I produce a bio-based raw material, considering it can be used in multiple consecutive life cycles, to generate environmental benefits? (e.g. comparative consequential LCA)

These questions may be asked by producers of raw materials that can be used in multiple life cycles, or by actors that aim to implement a circular economy system interlinking multiple stakeholders across life cycles (e.g. policymakers, CE coordinators, etc.).

12.6.2.2 Functional unit

At first hand, the functional unit will cover all of the products generated across the loops of the circular scenario (e.g. all the amount of recycled product generated over X number of loops). When comparing with alternatives, e.g. linear life cycles, care must be taken to formulate the same set of product functionalities.

12.6.2.3 System boundaries

The system boundaries cover all loops of the circular scenario. This is illustrated in Figure 30. Note that, if a linear system does not cover the same product functionalities over multiple life cycles as a circular system, the linear should model multiple independent product systems within its system boundaries. This is illustrated for the landfilling scenario in Figure 30.



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Figure 30. System boundaries of different scenarios for cellulose insulation, considering multiple loops.

12.6.3 Introduction to the FLOREC-BASIC tool

The FLOREC-BASIC tool (Schaubroeck et al. 2021a) is an Excel-based tool that applies primarily a system-based life cycle approach where the number of loops is modelled along a single pathway over time. Various parameters can be altered and results obtained, as shown in Figure 31. A priori, this modelling framework follows the system over time with functions differentiated over time. As such, the framework can present the impact of the overall systems and the collection of products over time, therefore applying a system/process-based approach with the application of functional unit expansion as a solution to model the multifunctionality of a circular system. A comparison with a linear system that provides the same products over the same time steps anew is covered.

The main research question that is addressed by the tool is: “What is the environmental impact (and cost) over time for this newly produced product that follows a circular pathway with finite loops compared to a conventional linear one?”. The consequential version would assess the impacts of a new additional production of that product, whereas the attributional version would evaluate the system as it is.

The system is followed in a supply-driven manner, only considering physical, energy or service flows. For example, for a given newly produced recyclable product, its subsequent loops of recycling are assessed considering efficiencies per process step. It thus originally follows a producer perspective.

The derived system is valid for both attributional and consequential LCA (respective background databases can be used). Impacts per process are summed, retrieved from background databases. This all implies that, as is now, differentiation over time and loop modelling is only done for the considered foreground system for one circular pathway.

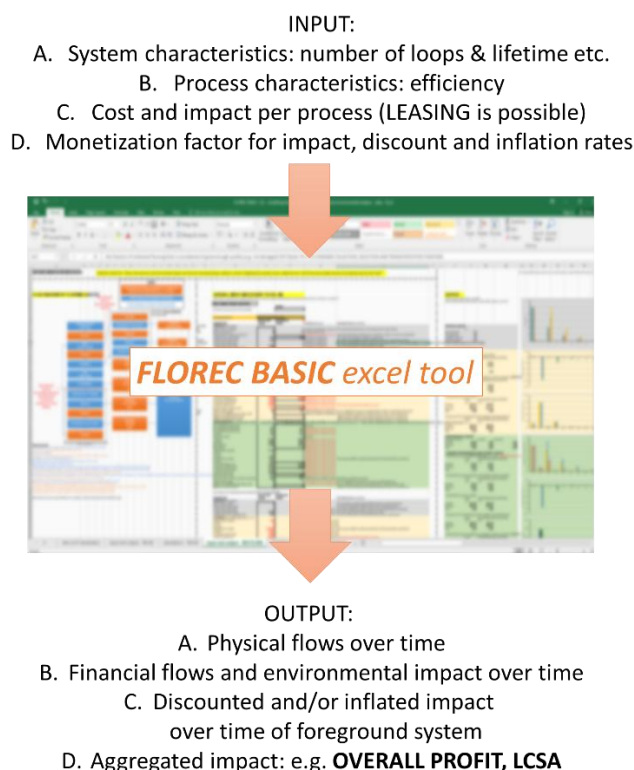


Figure 31. An overview of the input and output parameters of the FLOREC BASIC tool

The FLOREC BASIC tool can be applied for any sustainability impact type (covering thus also LCC, E-LCA, S-LCA & LCSA) as it mainly models the inventory of the foreground CE system. It has been tailored to consider also financial flows, monetization and coverage of time-related effects such as discounting and inflation. In practice, for each process within the system boundaries, impact amounts need to be specified, which could refer to any type of sustainability impact.

The tool has restrictions. It is mainly based on a flooring system, and also includes a possibility to consider a second closed loop of installation waste recycling. Application and adaptation to other systems is readily possible, but only one pathway of loops is considered.

12.6.4 Limitations of Multi-life cycle approach

The following limitations have been observed regarding the system expansion applied to multiple life cycles:

- 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.

12.6.5 Potential complementary methods or Circularity Indicators

Based on the circularity parameters covered by system expansion applied to multiple life cycles, the following circularity strategies may result in a beneficial effect of the product assessment using this approach:

- Increase recycled content
- Increase EoL recycling rate
- Increase EoL energy recover rate
- Minimize quality degradation
- Increase the functional characteristics of the produced recycled material at the end of life
- Increase reuse
- Decrease impacts of the recycling process of the recycled content
- Decrease impacts of the recycling process at the end of life
- Decrease impacts of primary raw material production
- Decrease impacts of the energy recovery process
- Decrease impacts of waste disposal
- Increase the efficiency of the energy recovery process
- Increase the energy content of the material
- Enable the use of a material in multiple loops in cascades
- Decrease impacts of downstream effects due to the substitution of a primary material
- Increase the efficiency of the recycling process at the EoL
- Increase the fraction of an EoL material that is collected for composting
- Increase the efficiency of the recycling process for the recycled content
- Increase the fraction of biological materials used which originate from Sustained Production
- Increase the fraction of a material collected for recycling at EoL
- Increase the fraction of a material collected for component reuse
- Increase the average number of uses of a material
- Increase the number of different users of a product during its use phase (via sharing/leasing)
- Decrease the mass of unrecoverable waste going to landfilling
- Decrease the mass of unrecoverable waste produced during recycling process at the end of life
- Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content
- Increase the share of reused content in a product
- Increase the share of renewable content in a product
- Limit water use to circular sources (i.e. renewable or recyclable)
- Increase the circular use of water
- Maximize on-site water circulation
- Increase the share of renewable energy use
- Increase the refurbishing rate
- Increase the remanufacturing rate

However, other circularity strategies may not result in noticeable benefits while applying system expansion with a focus on multiple life cycles, as this method does not include their quantification. Therefore, the assessment methods or circularity indicators listed in Table 26 can be used to provide this complementary information.

Table 26. Complementary assessment methods to evaluate the benefits of circularity strategies that are not covered by System expansion applying the recycler/valorizer perspective.

Circularity strategies not covered by the methodology	Comparative assessment with System expansion – Multiple life cycles	PEF Guide	EN 15804	APOS	CLCA	System expansion – Recycling perspective	MCI	CTI	ISO 59020:2024
Increase impacts of substituted primary raw material production	Yes	Yes	Yes		Yes	Yes		Yes	
Avoid primary energy sources with high environmental impacts	Yes	Yes	Yes		Yes	Yes			
Increase the lifetime of a product	Yes						Yes	Yes, optionally	Yes, optionally
Avoid waste treatment with high environmental impacts	Yes				Yes				
Avoid other valorisation processes with high environmental impacts	Yes				Yes				
Use recycled materials with low economic value/low demand		Yes		Yes	Yes				
Produce recycled materials with high economic value/high demand		Yes		Yes	Yes				
Produce recovered energy with high economic value/high demand		Yes		Yes	Yes				
Use recovered energy with low economic value/low demand				Yes	Yes				
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery							Yes	Yes	
Maximize the recovery potential up to theoretical limits								Yes, optionally	Yes

Circularity strategies not covered by the methodology	Comparative assessment with System expansion – Multiple life cycles	PEF Guide	EN 15804	APOS	CLCA	System expansion – Recycling perspective	MCI	CTI	ISO 59020:2024
Use less critical raw materials								Yes, optionally	
Increase the revenue generated relative to the total mass of linear resource inflows								Yes, optionally	Yes, optionally
Limit the increase in resource consumption compared to the increase of GDP									Yes, optionally

13 SYNTHESIS AND ANALYSIS OF MODELLING METHODS FOR CIRCULAR SYSTEMS IN LCA

13.1 LCA method selection for modelling of circularity strategies

From the previous section it became clear that there are multiple LCA approaches that can be used to model circularity aspects of a product and its life cycle. Each LCA approach has a different way to model a product's circularity, resulting potentially in large differences between the impacts assessed by the methods. Key aspects that justify the selection of one approach over another are aspects of the Goal and Scope definition of the LCA, starting with the scope of the assessed system. In this report, three scopes of assessed systems are identified. For each of these scopes, further refinement of the goal and scope definition enables the selection of a circularity modelling approach, as indicated in the linked figures:

1. Life cycle of a product (Figure 32)
2. Specific process(es) within the life cycle of a product (e.g. the recycling chain) (Figure 33)
3. Multiple subsequent life cycles (Figure 34)

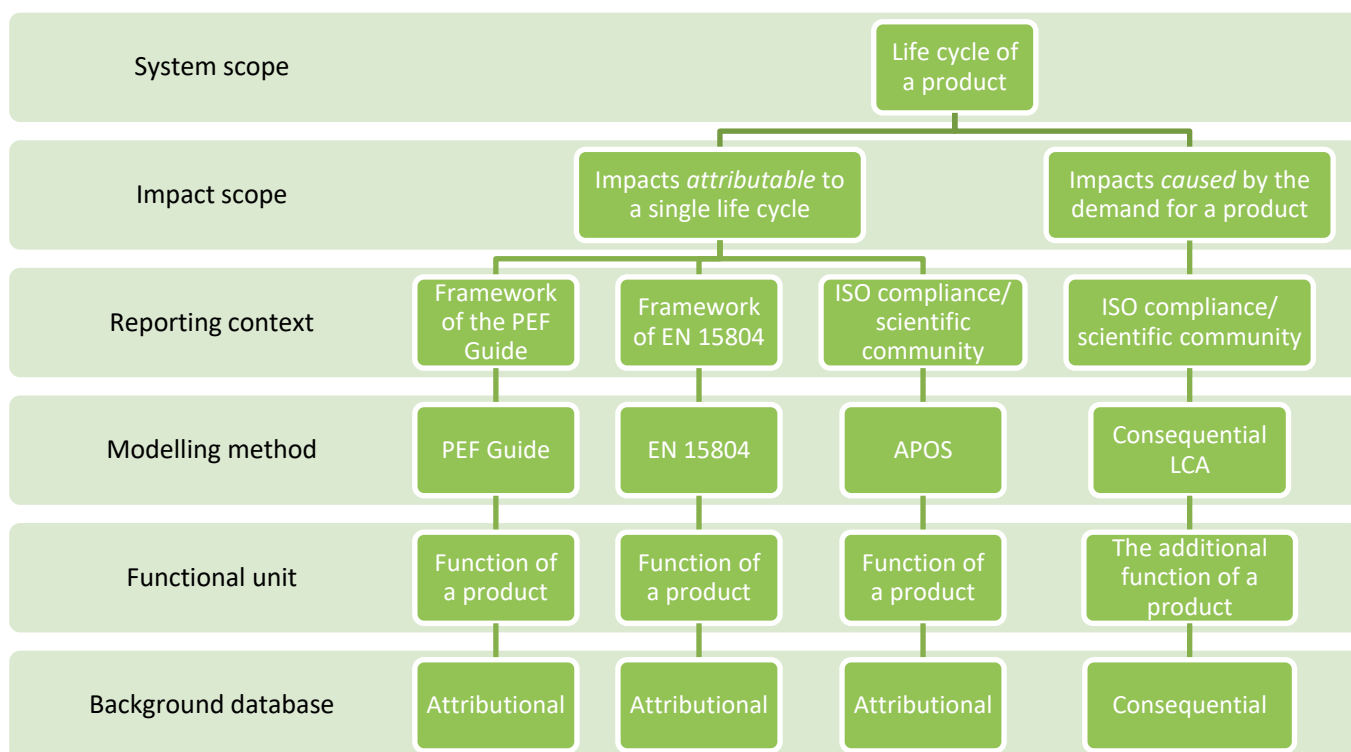


Figure 32. LCA method selection for studies focusing on the life cycle of a product

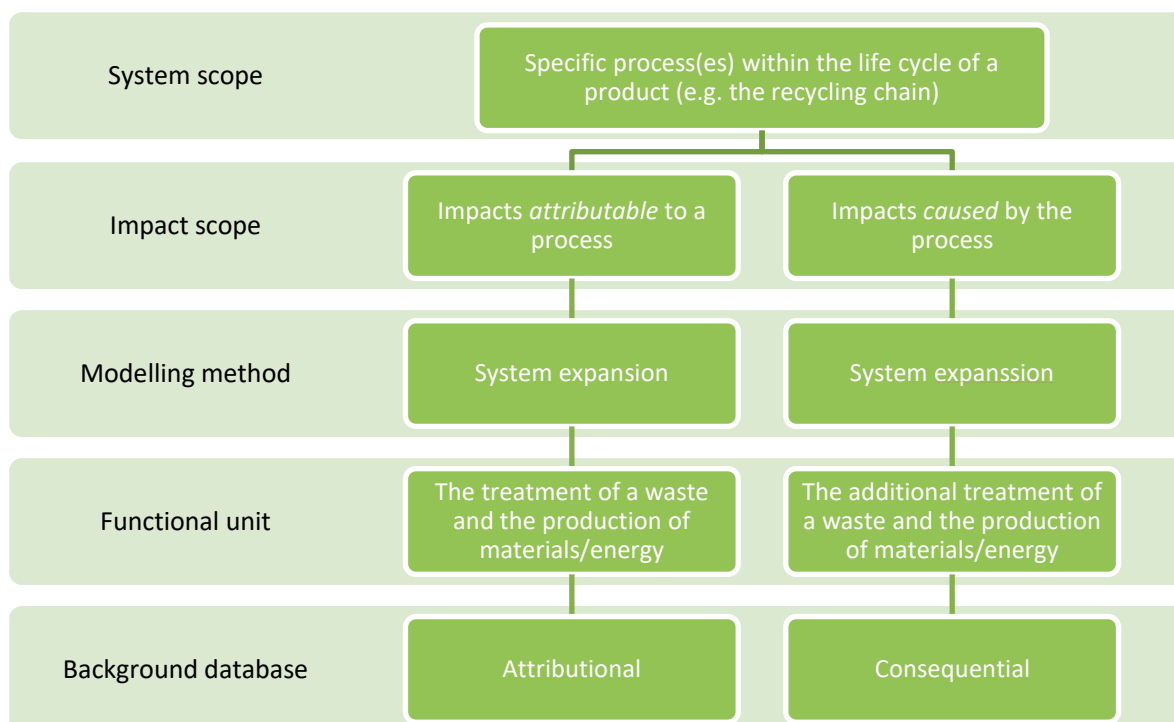


Figure 33. LCA method selection for studies focusing on selected processes within a life cycle.

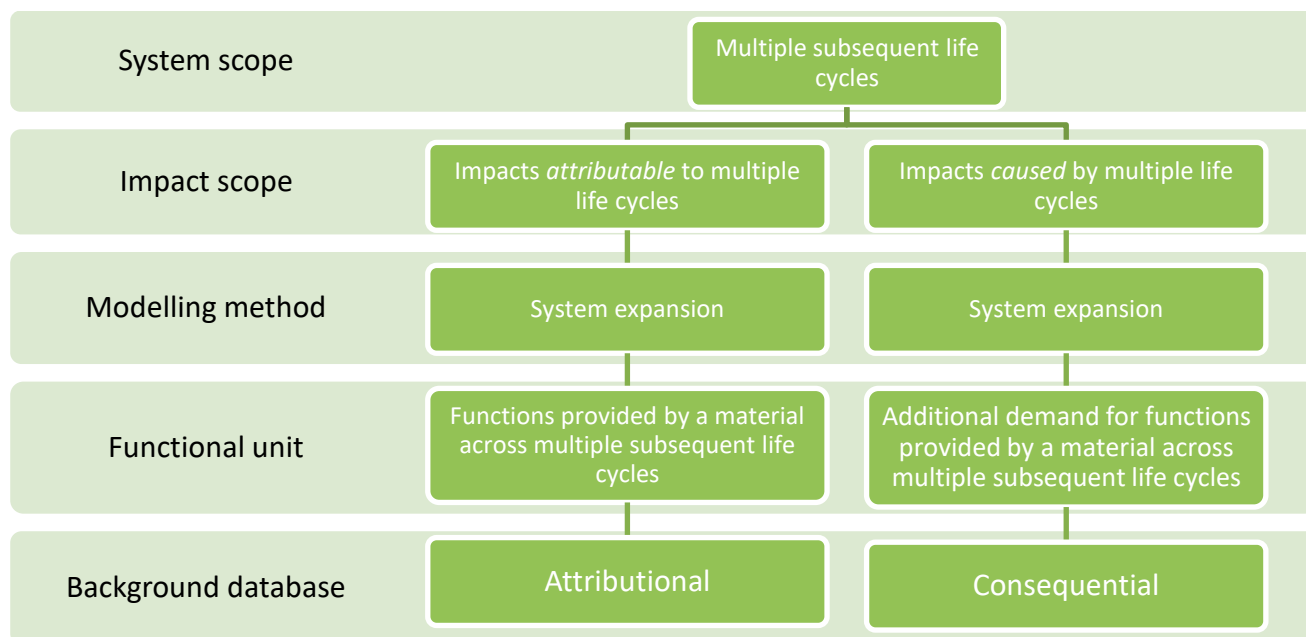


Figure 34. LCA method selection for studies taking multiple life cycles into account.

13.2 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 are able to demonstrate the benefits of all circularity strategies. An overview of which circularity strategies are covered by which method is provided in Table 27. 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 the Annex 1. A graphical representation of Table 27 is provided in Figure 35, Figure 36 and, displaying the coverage of the circularity parameters in the different LCA and circularity methods. An interactive version of this network version 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 application of system expansion from the perspective of the recycler is the most restrictive method (covering only 13 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 represent a certain circularity strategy that is however implemented by the stakeholder that is interested in the results of the study. Then, a complementary assessment may be conducted to represent the additional benefits generated by this specific circularity strategy. In section 11.3, complementary assessment methods or Circularity Indicators are indicated for each LCA modelling method, and for each circularity strategy. For example, if the PEF Guide is followed to assess the environmental impacts of a product that is recyclable at the end of life, the potential benefit of enabling the use of a material in 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 done in this area (see also Figure 37).

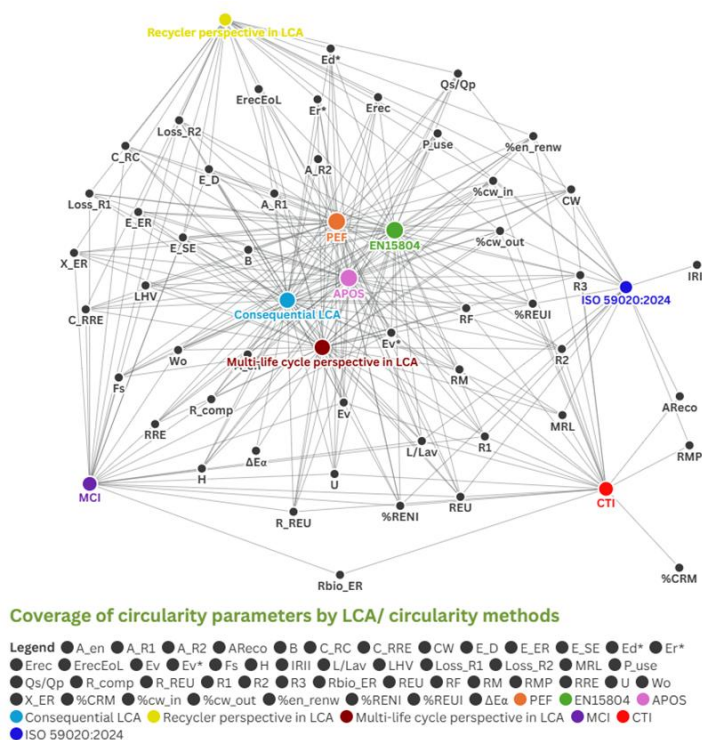


Figure 35. Coverage of circularity parameters in different LCA methods and stand-alone Circularity Indicators. A legend of the abbreviations is provided in Table 27.

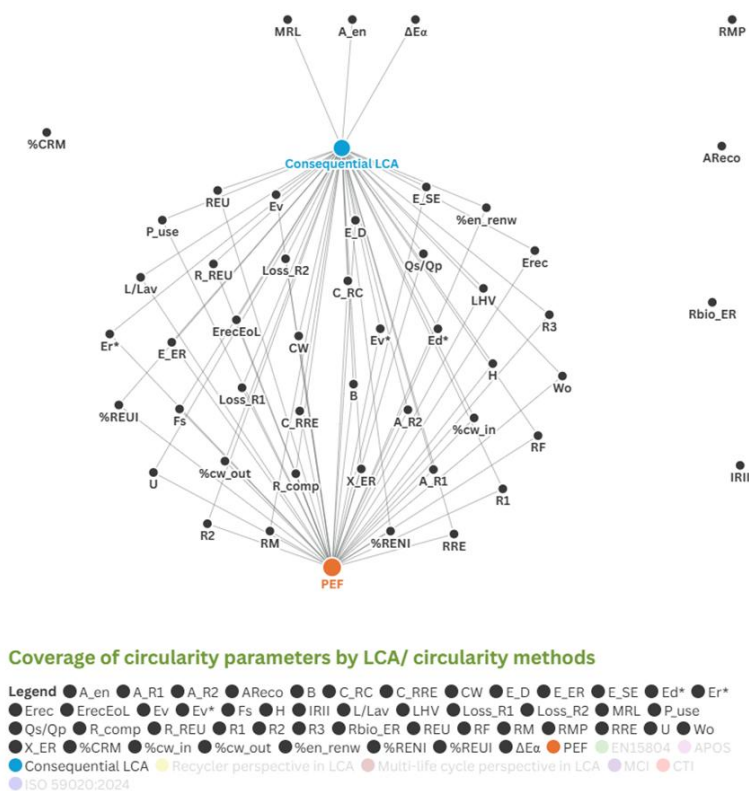


Figure 36. Coverage of circularity parameters in the consequential LCA method and the PEF Guide. A legend of the abbreviations is provided in Table 27.

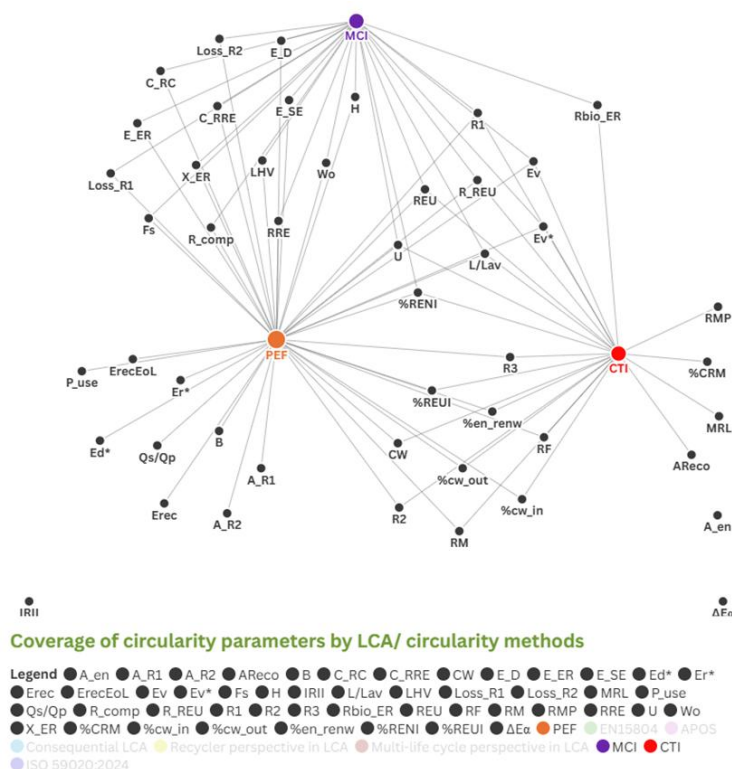


Figure 37. Coverage of circularity parameters in the PEF Guide and the stand-alone Circularity Indicators MCI and CTI. A legend of the abbreviations is provided in Table 27.

Table 27. Legend of circularity parameters for Figure 35, Figure 36 and Figure 37.

Acronym	Circularity parameter
A_en	Market situation of consumed recovered energy
A_R1	Market situation of a consumed recycled material
A_R2	Market situation of a produced recycled material
AReco	Actual recovery rate relative to the theoretical recovery potential
B	Market situation of produced recovered energy
C_RC	Efficiency of the recycling process for the recycled content
C_RRE	Efficiency of the recycling process at the EoL
CW	On-site water circulation (reuse & recycle)
E_D	Impacts of waste disposal without energy/raw material recovery
E_ER	Impacts of the energy recovery process
E_SE	Impacts of the substituted energy source
Ed*	Impacts of a substituted waste treatment process
Er*	Impacts of a substituted valorisation process
Erec	Impacts of the recycling process for the recycled content

Acronym	Circularity parameter
ErecEoL	Impacts of the recycling process at the end of life
Ev	Impacts of the consumed primary raw material
Ev*	Impacts of the substituted production of primary raw materials
Fs	Fraction of biological materials used which originate from Sustained Production
H	Number of times a product is hired (multiple consumers during the use phase)
IRII	Resource intensity index
L/Lav	Average lifetime of a product or material relative to an industry average
LHV	Energy content of material
Loss_R1	Mass of unrecoverable waste generated during the recycling process for the recycled content
Loss_R2	Mass of unrecoverable waste generated during the recycling process at EoL
MRL	Multiple recycling loops in cascades
P_use	Potential uses of a produced recycled material (considering functionality and quality requirements)
Qs/Qp	Quality degradation of recycled material
R_comp	Fraction of the product being collected to go into a composting process
R_REU	Fraction of the product going to component reuse
R1	Recycled content
R2	End-of-life recycling rate
R3	End-of-life energy recovery rate
Rbio_ER	Fraction of the product comprising biological materials from Sustained Production going to energy recovery
REU	Reuse rate in closed loop
RF	Refurbishing rate
RM	Remanufacturing rate
RMP	Material productivity
RRE	Fraction of the product being collected for recycling at EoL
U	Average number of cycles of a product or material for the defined use phase relative to an industry average
Wo	Mass of unrecoverable waste of product going into landfill, waste to energy
X_ER	The efficiency of the energy recovery process
%CRM	Fraction of the total material/product considered a critical raw material
%cw_in	Per cent of water demand that is derived from circular sources
%cw_out	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
%en_renw	Share of energy consumed that is renewable energy
%RENI	Renewable material content
%REUI	Reused content
ΔE_a	Downstream effects of recycling in the subsequent life cycle, beyond the substitution of primary raw materials (e.g. differences in transport, use and EoL)

It can be observed that there is much overlap between the circularity strategies covered in most LCA methods. However, there are a few circularity strategies that are only covered by Circularity Indicators:

- Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery
- Maximize the recovery potential up to theoretical limits
- Increase the revenue generated relative to the total mass of linear resource inflows
- Use less critical raw materials
- Limit the increase in resource consumption compared to the increase of GDP

Companies or other stakeholders wishing to demonstrate the benefits of their efforts on these circularity aspects would benefit from using Circularity Indicators as complementary information to LCA results. For these specific circularity strategies, a combination of CTI and ISO 59020 may be recommended. MCI shows more overlap with other LCA approaches, except for system expansion from the recycler's perspective, where it can be used as a complementary evaluation approach.

Table 28. Coverage of circularity strategies by LCA methods and Circularity Indicators. Circularity strategies are sorted by the number of methods that cover them. Count of circularity strategies include "Yes" and "Yes, optionally". A full table with nuanced assessment scores is given in the Annex 1.

Related circularity strategy to decrease impacts	PEF	EN15804	APOS	Consequential LCA	Recycler perspective in LCA	Multi-life cycle perspective in LCA	MCI	CTI	ISO 59020:2024	Number of methods covering circularity strategy (Yes)	Number of methods covering circularity strategy (yes, optionally)	Number of methods covering circularity strategy
Increase recycled content	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	8	0	8
Increase reuse	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	8	0	8
Increase the share of renewable content in a product		Yes	Yes	Yes		Yes	Yes	Yes	Yes	8	0	8
Limit water use to circular sources (i.e. renewable or recyclable)	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes, optionally	7	1	8
Increase the circular use of water	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes, optionally	7	1	8
Increase the share of renewable energy use	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes, optionally	7	1	8
Maximize on-site water circulation	Yes	Yes	Yes	Yes	Yes	Yes		Yes, optionally	Yes, optionally	6	2	8
Increase EoL recycling rate	Yes	Yes	Yes	Yes		Yes		Yes	Yes	7	0	7
Increase EoL energy recover rate	Yes	Yes	Yes	Yes		Yes		Yes	Yes	7	0	7
Increase the efficiency of the energy recovery process	Yes	Yes	Yes	Yes	Yes	Yes	Yes			7	0	7

Increase the energy content of the material	Yes	Yes	Yes	Yes	Yes	Yes	Yes		7	0	7	
Increase the efficiency of the recycling process at the EoL	Yes	Yes	Yes	Yes	Yes	Yes	Yes		7	0	7	
Increase the efficiency of the recycling process for the recycled content	Yes	Yes	Yes	Yes	Yes	Yes	Yes		7	0	7	
Increase the fraction of a material collected for component reuse	Yes	Yes	Yes	Yes		Yes	Yes	Yes	7	0	7	
Increase the average number of uses of a material	Yes	Yes	Yes	Yes		Yes	Yes	Yes	7	0	7	
Decrease the mass of unrecoverable waste produced during recycling process at the end of life	Yes	Yes	Yes	Yes	Yes	Yes	Yes		7	0	7	
Decrease the mass of unrecoverable waste produced during the recycling process of the recycled content	Yes	Yes	Yes	Yes	Yes	Yes	Yes		7	0	7	
Increase the share of reused content in a product	Yes	Yes	Yes	Yes		Yes		Yes	Yes	7	0	7
Minimize quality degradation	Yes	Yes	Yes	Yes	Only in a comparative assessment	Yes		Yes	6	0	6	
Decrease impacts of the recycling process of the recycled content	Yes	Yes	Yes	Yes	Yes	Yes			6	0	6	
Decrease impacts of the recycling process at the end of life	Yes	Yes	Yes	Yes	Yes	Yes			6	0	6	
Decrease impacts of primary raw material production	Yes	Yes	Yes	Yes	Only in a comparative assessment	Yes		Yes	6	0	6	

Decrease impacts of the energy recovery process	Yes	Yes	Yes	Yes	Yes	Yes			6	0	6
Increase the fraction of an EoL material that is collected for composting	Yes	Yes	Yes	Yes		Yes	Yes		6	0	6
Increase the fraction of biological materials used which originate from Sustained Production	Yes	Yes	Yes	Yes		Yes	Yes		6	0	6
Increase the fraction of a material collected for recycling at EoL	Yes	Yes	Yes	Yes		Yes	Yes		6	0	6
Increase the number of different users of a product during its use phase (via sharing/leasing)	Yes	Yes	Yes	Yes		Yes	Yes		6	0	6
Decrease the mass of unrecoverable waste going to landfilling	Yes	Yes	Yes	Yes		Yes	Yes		6	0	6
Increase the refurbishing rate	Yes	Yes	Yes	Yes		Yes		Yes	6	0	6
Increase the remanufacturing rate	Yes	Yes	Yes	Yes		Yes		Yes	6	0	6
Increase the functional characteristics of the produced recycled material at the end of life	Yes	Yes	Only in a comparative assessment	Yes	Only in a comparative assessment	Yes		Yes	5	0	5
Decrease impacts of waste disposal	Yes	Yes	Yes	Yes	Only in a comparative assessment	Yes			5	0	5
Increase impacts of substituted primary raw material production	Yes	Yes	Only in a comparative assessment	Yes	Only in a comparative assessment	Only in a comparative assessment		Yes	4	0	4
Enable the use of a material in multiple loops in cascades			Yes	Yes		Yes		Yes	4	0	4

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY												
Use recycled materials with low economic value/low demand	Yes		Yes	Yes					3	0	3	
Produce recycled materials with high economic value/high demand	Yes		Yes	Yes					3	0	3	
Produce recovered energy with high economic value/high demand	Yes		Yes	Yes					3	0	3	
Avoid primary energy sources with high environmental impacts	Yes	Yes	Only in a comparative assessment	Yes	Only in a comparative assessment	Only in a comparative assessment			3	0	3	
Increase the lifetime of a product	Only in a comparative assessment			Only in a comparative assessment for functional unit. Included for substituted products		Only in a comparative assessment	Yes	Yes, optionally	Yes, optionally	1	2	3
Use recovered energy with low economic value/low demand			Yes	Yes					2	0	2	
Decrease impacts of downstream effects due to the substitution of a primary material				Yes		Yes			2	0	2	
Increase the fraction of the product comprising biological materials from Sustained Production going to energy recovery							Yes	Yes		2	0	2
Maximize the recovery potential up to theoretical limits								Yes, optionally	Yes	1	1	2
Increase the revenue generated relative to the total mass of linear resource inflows								Yes, optionally	Yes, optionally	0	2	2

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY									
Avoid waste treatment with high environmental impacts	Only in a comparative assessment	Yes	Only in a comparative assessment	Only in a comparative assessment			1	0	1
Avoid other valorisation processes with high environmental impacts	Only in a comparative assessment	Yes	Only in a comparative assessment	Only in a comparative assessment			1	0	1
Use less critical raw materials					Yes, optionally		0	1	1
Limit the increase in resource consumption compared to the increase of GDP						Yes, optionally	0	1	1

14 ASSESSMENT OF CIRCULARITY STRATEGIES IN S-LCA AND LCC/ ECONOMIC LCA

Analyzing the economic and social performance of circularity strategies is paramount to ensuring overall sustainable performance when addressing a specific circularity framework. In addition, the social and economic dimensions are also important to be taken into account in order to avoid burden shifting with environmental impacts. This section provides an overview of the state of the art in the economic and social evaluation of circularity strategies following a life-cycle perspective, based on a literature review of scientific articles. This review was conducted using the Scopus database and was guided by a set of keywords. The first search iteration yielded a total of 61 publications using the following combination of keywords:

- circularity AND ("S-LCA" OR "social life cycle assessment")
- (s-lca OR "social assessment" OR "social performance" OR "social life cycle assessment") AND (circularity OR "circularity strategies")
- ("circularity strategies" OR circularity) AND (lcc OR "life cycle costing")

An additional search was performed using the combination of keywords: (s-lca OR "social life cycle assessment") AND (circularity OR "circularity strategies" OR reduce OR cascading OR "energy recovery" OR recycling OR reuse OR reduce OR "close loop" OR repair OR refurbish OR repurpose OR recovery OR composting OR valorisation OR mulching), this time restricting the results to those published after 2018 (year not included) in order to limit the number of results obtained to a manageable but representative number (62 results). A total of 123 publications were identified in this first phase, which were then reduced to 31 articles after a screening process in which publications were either excluded because they were duplicates, out of scope (e.g. did not cover a circularity strategy), focused only on the environmental dimension, conceptual in nature or did not represent social or economic methodological implications.

The selected articles were then subjected to an in-depth analysis to extract relevant information, including the circularity strategies covered, the social and economic aspects assessed, the methodological approaches followed, the challenges/limitations and benefits of the analysis, as well as their insights into future perspectives.

The list of articles reviewed collected in Table 29 shows that up to 11 different sectors have been analyzed from a social or economic point of view using a life cycle approach (i.e., S-LCA or LCC, respectively), coupled with different circular economy strategies: (i) chemical, (ii) plastic, (iii) waste, (iv) energy, (v) agri-food, (vi) water production, (vii) technology, (viii) construction, (ix) furniture, (x) textiles and (xi) events.

Of the sectors identified, the waste sector is by far the most common in the sample of articles analyzed, appearing in almost half of them (15), followed by energy and construction (6 each). The agri-food sector (3 articles), chemicals and plastic (2 each) are much less represented, while the rest are represented by only one article.

Focusing now on the five bio-based sectors targeted by the CALIMERO project (i.e., biochemicals, construction, woodworking, textiles and pulp & paper), of the two papers related to the chemical sector, neither is classified as bio-based. The first paper evaluated green methanol produced with CO₂ (directly captured from the air) and hydrogen from wind power electrolysis (Iribarren et al., 2022), while the other was based on the assessment of the impact of recycling high-density polyethylene non-beverage bottles (Papo and Corona, 2022). In the construction sector, up to six articles deal with activities related to the adaptive reuse of existing

buildings and shared spaces (Lundgren, 2023), the reuse of materials related to trenches for the protection of services such as water and gas pipelines (Josa et al., 2023), construction and demolition waste management of concrete and timber houses (Tanthanawiwat et al., 2024), the service life of residential buildings (Janjua et al., 2019) and football stadiums (Kucukvar et al., 2021), apart from circular building proposals (Rajagopalan et al., 2021). Regarding the woodworking sector, a paper has been identified that analyzes three companies, one of which is a supplier of furniture like cupboards and recycling stations for public spaces (Kambanou and Sakao, 2020). Lastly, only one paper is related to the textiles sector, which examines a sweater production process using the discarded wool from a sheep farm in a Swedish town (Martin and Herlaar, 2021). Consequently, based on the above it can be said that four out of the five-target bio-based sectors in the CALIMERO project have been already addressed: bio-chemicals, construction, woodworking and textiles, while the pulp & paper sector remains unexplored within the scope of the search.

Moving on the socio-economic life cycle indicators used in the set of articles examined. On the one hand, in terms of LCC, the Life Cycle Cost (LCC) indicator is the most represented, appearing in up to 15 of them. In second place is the assessment of external costs and revenues, each of which appears in 5 articles. Likewise, 3 articles addressed additional economic indicators in terms of Internal Rate of Return (IRR), Levelized Cost of Production (LCOP) or Payback Period (PP). Lastly, only one article addresses the discounted gross margin. These figures are consistent with the findings of Arulnathan et al. (2022), who reported that gross margin/net profit, Net Present Value (NPV), and IRR are ones of the most commonly used economic indicators when conducting an LCSA. On the other hand, in relation to the Social Life Cycle Impact Assessment (SLCIA) considered, the reference scale (i.e., type 1) is more used in comparison with the impact pathway (i.e., type 2) approach (14 and 6 articles, respectively). For more information in this regard, please take a look to D3.5. Concerning social stakeholders studied, workers (16), society (13), consumers (12) and local community (12) are the most evaluated, while value chain actors (8) and children (3) are secondary. Therefore, from these figures, it can be concluded that as far as the SLCIA selected is concerned, the predominance of type I versus type II is in line with the statement that one of the limitations of S-LCA is the qualitative nature of social effects, generating difficulties when it is desired to evaluate them in a quantitative manner (UNEP et al., 2021). The same is true for the social stakeholder "worker", as it has proven to be the most studied, especially for the bioeconomy (Rebolledo-Leiva et al., 2023), after having identified a considerable amount of case studies that can be categorized within the set of articles reviewed.

Table 29. Authors, title, year and DOI of the reviewed articles.

Authors	Title	Year	DOI
Mura R.; Vicentini F.; Botti L.M.; Chiriaco M.V.	Achieving the circular economy through environmental policies: Packaging strategies for more sustainable business models in the wine industry	2024	10.1002/bse.3556
Tanthanawiwat K.; Gheewala S.H.; Nilsalab P.; Schoch M.; Silalertruksa T.	Environmental sustainability and cost performances of construction and demolition waste management scenarios: A case study of timber and concrete houses in Thailand	2024	10.1016/j.jclepro.2024.140652
Ardolino F.; Palladini A.; Arena U.	Social life cycle assessment of innovative management schemes for challenging plastics waste	2023	10.1016/j.spc.2023.03.011
Baltrocchi A.P.D.; Ferronato N.; Calle Mendoza I.J.; Gorritty Portillo M.A.; Romagnoli F.; Torretta V.	Socio-economic analysis of waste-based briquettes production and consumption in Bolivia	2023	10.1016/j.spc.2023.03.004
Ghisellini P.; Passaro R.; Ulgiati S.	Environmental and Social Life Cycle Assessment of Waste Electrical and Electronic Equipment Management in Italy According to EU Directives	2023	10.3390/environments10070106
Josa I.; Garfi M.	Social life cycle assessment of microalgae-based systems for wastewater treatment and resource recovery	2023	10.1016/j.jclepro.2023.137121

Josa I.; Petit-Boix A.; Casanovas-Rubio M.M.; Pujadas P.; de la Fuente A.	Environmental and economic impacts of combining backfill materials for novel circular narrow trenches	2023	10.1016/j.jenvman.2023.118020
Lundgren R.	Social life cycle assessment of adaptive reuse	2023	10.5334/bc.314
Parchomenko A.; De Smet S.; Pals E.; Vanderreydt I.; Van Opstal W.	The circular economy potential of reversible bonding in smartphones	2023	10.1016/j.spc.2023.08.017
Phuang Z.X.; Woon K.S.; Mong G.R.; Hanafiah M.M.; Liew P.Y.	Assessing Plastic Waste Green Economy Management via Integrated Life Cycle Environmental and Costing Framework	2023	10.3303/CET23106019
Sundin N.; Bartek L.; Persson Osowski C.; Strid I.; Eriksson M.	Sustainability assessment of surplus food donation: A transfer system generating environmental, economic, and social values	2023	10.1016/j.spc.2023.03.022
Tarpani R.R.Z.; Azapagic A.	Life cycle sustainability assessment of advanced treatment techniques for urban wastewater reuse and sewage sludge resource recovery	2023	10.1016/j.scitotenv.2023.161771
Tsalidis G.A.; Xevgenos D.; Ktori R.; Krishnan A.; Posada J.A.	Social life cycle assessment of a desalination and resource recovery plant on a remote island: Analysis of generic and site-specific perspectives	2023	10.1016/j.spc.2023.03.017
Falcone G.; Stillitano T.; Iofrida N.; Spada E.; Bernardi B.; Gulisano G.; De Luca A.I.	Life cycle and circularity metrics to measure the sustainability of closed-loop agri-food pathways	2022	10.3389/fsufs.2022.1014228
Iribarren D.; Calvo-Serrano R.; Martín-Gamboa M.; Galán-Martín Á.; Guillén-Gosálbez G.	Social life cycle assessment of green methanol and benchmarking against conventional fossil methanol	2022	10.1016/j.scitotenv.2022.153840
Nubi O.; Morse S.; Murphy R.J.	Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study	2022	10.3390/en15239173
Papo M.; Corona B.	Life cycle sustainability assessment of non-beverage bottles made of recycled High Density Polyethylene	2022	10.1016/j.jclepro.2022.134442
Nubi O.; Morse S.; Murphy R.J.	Prospective Life Cycle Costing of Electricity Generation from Municipal Solid Waste in Nigeria	2022	10.3390/su142013293
Nubi O.; Morse S.; Murphy R.J.	A Prospective Social Life Cycle Assessment (sLCA) of Electricity Generation from Municipal Solid Waste in Nigeria	2021	10.3390/su131810177
Kambanou M.L.; Sakao T.	Using life cycle costing (LCC) to select circular measures: A discussion and practical approach	2020	10.1016/j.resconrec.2019.104650
Shaikh S.; Thomas K.; Zuhair S.; Magalini F.	A cost-benefit analysis of the downstream impacts of e-waste recycling in Pakistan	2020	10.1016/j.wasman.2020.08.039
Tsalidis G.A.; Gallart J.J.E.; Corberá J.B.; Blanco F.C.; Harris S.; Korevaar G.	Social life cycle assessment of brine treatment and recovery technology: A social hotspot and site-specific evaluation	2020	10.1016/j.spc.2020.02.003
Cobo S.; Levis J.W.; Dominguez-Ramos A.; Iribarren A.	Economics of Enhancing Nutrient Circularity in an Organic Waste Valorisation System	2019	10.1021/acs.est.8b06035
Janjua S.Y.; Sarker P.K.; Biswas W.K.	Sustainability assessment of a residential building using a life cycle assessment approach	2019	10.3303/CET1972004
Opher T.; Friedler E.; Shapira A.	Comparative life cycle sustainability assessment of urban water reuse at various centralization scales	2019	10.1007/s11367-018-1469-1
Tsalidis G.A.; Korevaar G.	Social life cycle assessment of brine treatment in the process industry: A consequential approach case study	2019	10.3390/su11215945
Kucukvar M.; Kutty A.A.; Al-Hamrani A.; Kim D.; Nofal N.; Onat N.C.; Ermolaeva P.; Al-Ansari T.; Al-Thani S.K.; Al-Jurf N.M.; Bulu M.; Al-Nahhal W.	How circular design can contribute to social sustainability and legacy of the FIFA World Cup Qatar 2022™? The case of innovative shipping container stadium	2021	10.1016/j.eiar.2021.106665
Martin M.; Herlaar S.	Environmental and social performance of valorizing waste wool for sweater production	2021	10.1016/j.spc.2020.11.023
Martín-Gamboa M.; Quinteiro P.; Dias A.C.; Iribarren D.	Comparative social life cycle assessment of two biomass-to-electricity systems	2021	10.3390/ijerph18094918
Rajagopalan N.; Brancart S.; De Regel S.; Paduart A.; De Temmerman N.; Debacker W.	Multi-criteria decision analysis using life cycle assessment and life cycle costing in circular building design: A case study for wall partitioning systems in the circular retrofit lab	2021	10.3390/su13095124
Tian S.; Tang H.; Wang Q.; Yuan X.; Ma Q.; Wang M.	Evaluation and optimization of blanket production from recycled polyethylene terephthalate based on the coordination of environment, economy, and society	2021	10.1016/j.scitotenv.2021.145049

According to the three basic principles of circular economy proposed by Velenturf and Purnell (2021): (A) minimize external resource input, (B) optimize the production-consumption system and (C) maximize waste prevention, it was decided to classify the different circularity strategies identified during the review as follows: (i) input-oriented, (ii) system-oriented and (iii) output-oriented. Based on this classification, a series of circularity strategies were identified, having been compiled in Table 30. In addition, examples were given of the circularity strategies identified in the sample of articles reviewed. Looking at the circularity strategies, it can be said that most of them are focused on the inputs of the system, addressing different approaches based on the quantity (promote resource reduction) or characteristics (avoid virgin raw materials) that consider the origin (proximity supply chain system) of the material (commitment to use bio-based raw materials) or energy (rely on renewable energy) requirements. Conversely, only two output-oriented strategies were identified, based on the potential of the output produced to be recycled (promote recycling materials) or valorised (from waste to feedstock) in a subsequent system. A similar situation occurs for system-oriented strategies, which focus on promoting the reuse of materials, extending the lifespan of equipment and implement a reverse logistics system.

Table 30. Circularity strategies identified during the review process classified according to the three basic principles of circular economy.

Circular economy principles	Circularity strategies	Examples (references)
Input-oriented	Promote resource reduction	Reuse of waste as an alternative to replace some of the conventional cement used in construction (Janjua et al., 2019)
	Avoid virgin raw materials	Use of shipping containers as building materials for the construction of a football stadium (Kucukvar et al., 2021)
	Commitment to use bio-based raw materials	Biomass-to-electricity system based on fluidized-bed technology located in Portugal (Martín-Gamboa et al., 2021)
	Rely on renewable energy	Electricity provided from wind energy (Iribarren et al., 2022)
	Proximity supply chain system	Supply chain of waste wool from a Norway sheep farm to be used for sweater production (Martin and Herlaar, 2021)
System-oriented	Promote re-using materials	Construction material reuse as trenches for protecting services (Josa et al., 2023)
	Focus on extend the lifespan	Adhesives for reversible bonding in smartphones (Parchomenko et al., 2023)
Output-oriented	Reverse logistics system	Collection of used products (e.g., furniture) for repairing purposes (Kambanou and Sakao, 2020)
	Promote recycling materials	Enable subsequent recycling cycles applied to non-beverage bottle production (Papo and Corona, 2022)
	From waste to energy/feedstock	Energy recovery technologies (e.g., anaerobic digestion) (Nubi et al., 2022)

14.1 Identification of procedures for evaluating and integrating circularity strategies in S-LCA/LCC

The circularity strategies shown in Table 30 were related to a series of evaluation and integration procedures related to socio-economic life cycle assessments (i.e., LCC and/or S-LCA). The list of procedures for evaluating and integrating circular strategies into LCC and S-LCA has been compiled in Table 31, based on the general findings from the literature review, highlighting their main advantages and drawbacks.

Most of the articles reviewed focused on making direct comparisons between scenarios that integrate a circular strategy and scenarios that do not, applying LCC and/or S-LCA to them in order to measure circularity performance from a social and/or economic point of view. Although this approach provides easy-to-interpret and valuable results, the majority of circular economy case studies are based on hypothetical situations or secondary information. In addition, the issue of the multifunctionality is often encountered. For LCC, cost allocation is used for the activity, attributing direct costs and assigning indirect costs using cost drivers. In the case of recycling circular systems, when products have the same function, this can be overcome by considering a system extension approach, where subsequent recycling rates are taken into account in the recycling scenario (Papo and Corona, 2022). LCC and S-LCA have also been integrated into circular economy actions, measuring economic and social efficiency, taking into account benefit-cost ratios. This approach was identified in several scenarios and contexts, such as in a food waste management procedure to assess the socio-economic impact of food donation (Sundin et al., 2023), in a plastic waste recycling system (Phuang et al., 2023) or in an electronic waste recycling process located in Pakistan (Shaikh et al., 2020).

Table 31. Main advantages and disadvantages of evaluation and integration methods for circularity strategies in socio-economic life cycle assessments.

Socio-economic life cycle assessment	Evaluation and integration of circularity strategies	Pros	Cons
LCC and S-LCA	Suggest different scenarios based on the application of circularity strategies for sensitivity analysis and include them in the LCC/S-LCA to compare results with other circularity strategies or baseline scenarios	+ Easy to apply when you have prior knowledge on LCC/S-LCA + The results provide empirical evidence and highlight areas to improve economic/social implications	- No standardized methodologies for LCC/S-LCA, which makes it difficult to extrapolate the comparison with other studies conducted - Most analyses are not based on real case studies, but on hypothetical scenarios and assumptions based on literature
LCC and S-LCA	Evaluation of the economic/social efficiency of circular economy actions using a benefit-cost ratio	+ Easy to interpret + Potential for use in decision making or as a way for promoting green policies from an economic and social perspective	- No standard for carrying out LCC nor S-LCA - Environmental benefits are based on avoiding CO ₂ emissions and further impact categories should be considered by conducting social LCC
LCC	Assessment of the economic feasibility of the level of circularity	+ Easy to interpret + Potential for use in decision making or as a basis for feasible	- No standard for assessing the level of circularity nor LCC - It could go a step further in terms of representativeness by doing an integration of both

		economic circularity policies	concepts (LCC + circularity) by monetizing the circular strategies themselves
S-LCA	Definition of supply chains through the jointly use of life cycle inventories and trade databases, allowing to identify representative countries of origin for the unit processes involved in a product system	+ Enlarged system boundaries with multi-tier perspective + Enhanced social life cycle inventory + Allow to improve the supply chain from a social perspective and promote proximity	- Life cycle inventory analysis turns out to be a more time-consuming activity - Requirement of additional trade databases

Regarding LCC, an evaluation of the economic feasibility can be conducted in order to rate the circularity initiatives. In this sense, Kambanou and Sakao (2020) measure the economic value of refurbishing, repairing and redesigning material and digital visibility solutions, furniture and waste collection systems, respectively, compared with standard production processes fulfilling the same function. For S-LCA, the social impacts in units of medium risk hours (which means the number of hours associated with a medium level of social risk in terms of working conditions, safety, or human rights violations) were evaluated when analyzing the different routes that constitute the supply chain of a specific production system to be proposed as a potential circular economy initiative. This constitutes a good way to integrate environmental and social impacts within circular economy initiatives, as it allows a balance to be struck between a commitment to close supply chains (and therefore lower environmental impact) and socially responsible supply chains. It also provides a decision-making tool to bring additional factors beyond price to the table when selecting suitable suppliers (Martin and Herlaar, 2021). To consider trade-offs among different social aspects, more indicators should ideally be integrated into the decision-making process.

The main conclusion of the literature review conducted is that not many papers have tackled the difficult task of integrating social and economic performance in relation to circularity, and most of them are based on direct comparisons between the values obtained by different baseline scenarios and others that take into account specific circularity strategies. Therefore, particular attention should first be paid to refining current methodologies to address these concepts: both social and economic impacts according to a life-cycle perspective (i.e., S-LCA and LCC), as well as circularity metrics, in order to propose robust procedures that allow for the correct integration and interpretation of the results.

In addition, future studies should focus on identifying social and economic hotspots within circularity strategies, as there is currently limited understanding of which processes are most impactful. Research is also needed to evaluate the relevance of circular processes in comparison to the overall life cycle, specifically regarding their influence on social and economic aspects. Furthermore, the development of methodologies that effectively integrate various social and economic indicators will be crucial to understanding the complexities of trade-offs and synergies within circular economy frameworks. By addressing these gaps, researchers can provide deeper insights into the social and economic implications of circularity.

15 CONCLUSIONS

This report gives guidance to LCA practitioners in modelling circular product systems of the bioeconomy, considering the wide range of circularity strategies that can be applied to biobased materials. The selection of

an appropriate Life Cycle Assessment (LCA) approach to model circularity is inherently dependent on the goal and scope of the analysis. This report presents a structured framework to facilitate the selection of a modelling method, guided by key elements of the goal and scope definition.

Furthermore, the presented approach clarifies which modelling methodologies can be used or combined to demonstrate the potential benefits of implementing circularity strategies. Our analysis highlights that the coverage of circularity strategies varies significantly across LCA methods. Consequential LCA provides the most comprehensive coverage, encompassing a wide range of strategies, whereas system expansion with the recycler's perspective offers the least coverage. Each modelling method has inherent limitations, and, where appropriate, generic recommendations for suitable data sources have been provided to address these challenges.

To enhance the evaluation of circularity strategies, we identified complementary methods and stand-alone circularity indicators that can be employed alongside each LCA method. This integrated approach helps to reveal the potential benefits of specific strategies, ensuring a more holistic assessment.

However, the consideration of circularity strategies in socio-economic analyses remains in its infancy compared to the relatively mature environmental LCA methodology. Current socio-economic evaluations are primarily limited to scenario comparisons, with minimal advancement toward comprehensive integration. To truly claim a holistic view of sustainability while promoting a circular economy, future efforts must prioritize further development of the social and economic dimensions, while considering the limitations of environmental assessments. This balanced focus will be essential for driving meaningful progress toward a more sustainable and circular future.

16 MAIN CONCLUSIONS FROM THIS REPORT

This report highlights the complementary nature of circularity and criticality in evaluating bio-based materials in the context of a Life Cycle Sustainability Assessment (LCSA) framework, offering a holistic approach to sustainability. Both concepts address distinct, yet interconnected challenges related to resource use and supply stability, providing tools for improving the resilience and sustainability of bio-based product systems.

On the circularity front, the report presents a structured framework to guide LCA practitioners in modelling circular product systems, emphasizing the importance of aligning the chosen methodology with the study's goal and scope. By mapping circularity strategies to LCA methods, the analysis reveals the strengths and limitations of various modelling approaches, such as the broad coverage offered by consequential LCA and the targeted application of stand-alone indicators to complement traditional methods. Despite advances in environmental assessment, the integration of circularity into socio-economic analyses remains underdeveloped. Future efforts must address this gap to enable a balanced assessment of environmental, social, and economic dimensions, ensuring a comprehensive evaluation of circularity strategies in bio-based systems.

From a criticality perspective, the report introduces a tailored framework for assessing supply risks associated with both biotic and abiotic materials. This stepwise approach considers the economic stakeholder of interest, evaluates risks along the value chain, and identifies effective mitigation strategies. The framework emphasizes actionable insights over quantifiable scores, enabling stakeholders to understand the interplay of supply disruptions and their potential impacts. Practical recommendations for data use, including proxy data and

qualitative estimates, offer flexibility in addressing data gaps, particularly for biotic materials, where centralized data sources are less mature.

The interplay between circularity and criticality highlights opportunities for synergies. Circularity strategies can mitigate criticality risks by reducing dependency on scarce materials, promoting recycling, and encouraging the use of renewable resources. Conversely, criticality assessments can identify materials that warrant priority attention in circular economy strategies, guiding decision-making toward more resilient systems.

Looking ahead, integrating circularity and criticality frameworks within the LCSA paradigm requires further development of tools and methodologies, particularly for socio-economic assessments and the unique challenges of bio-based materials. Enhanced data availability and methodological consistency will be key to unlocking the full potential of these frameworks, driving progress toward a more sustainable, resilient, and circular bioeconomy.

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ANNEX 1

Criticality section

At the following [link](#), an overview of selected indicators to quantify the risk sources illustrated in Figure 9 is given, a short description of each indicator is provided and more details are given regarding the original use of the indicator, the company risk it contributes to, the relevance for metals and/or biobased materials, the relevance for different steps in the value chain, and potential data sources.

Furthermore, the Excel file provides a data collection template, and a results calculation based on country-specific indicator scores. The template is applied to the illustrative example in the main report.

Circularity section

A comprehensive list of circularity strategies was developed that could make products and/or processes more sustainable. Not all LCA methods are able to demonstrate the benefits of all circularity strategies. An overview of which circularity strategies are covered by which method is provided in Table 27. 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 the following [link](#).

ANNEX 2

Illustration of a conversation with ChatGPT 3.5 to identify potential data sources on current suppliers of wood residue to Spain:

Q: Where does Spain import wood residue from?

A: Spain imports wood residue primarily from several countries, including Portugal, France, and various countries in South America such as Brazil and Chile. The imports are often used for energy production, biofuels, and the manufacturing of wood-based products. The specific sources can vary based on availability, pricing, and trade agreements. For the most current and detailed information, you may want to check trade statistics from Spain's customs or local industry reports.

Q: Can you give me some sources where I can find this information?

A: Certainly! Here are some sources where you can find information on Spain's wood residue imports:

1. ****Eurostat****: The statistical office of the European Union provides detailed trade statistics between EU member states and other countries. You can search for data on wood imports by country.
- Website: [Eurostat](https://ec.europa.eu/eurostat)
2. ****FAOSTAT****: The Food and Agriculture Organization of the United Nations offers data on forestry products, including wood residue, trade statistics, and production information.
- Website: [FAOSTAT](http://www.fao.org/faostat/en/#home)
3. ****Spanish Ministry of Industry, Trade and Tourism****: You can find reports and statistics related to trade and industry in Spain, including the forestry sector.
- Website: [Ministerio de Industria, Comercio y Turismo](https://www.mincotur.gob.es)
4. ****Wood Markets****: This is a platform that publishes market reports and analyses regarding the wood products market. They may provide insights into import trends and statistics.
- Website: [Wood Markets](https://www.woodmarkets.com)
5. ****International Trade Centre (ITC)****: The ITC provides trade data and profiles that can help you understand import/export dynamics by country and product category.
- Website: [ITC Trade Map](https://www.trademap.org)
6. ****Research Journals****: Academic journals and industry research reports often publish studies on timber trade and wood products which may provide detailed insights.

By exploring these resources, you should be able to gather more specific and current data regarding Spain's imports of wood residue.