SWEDISH LIFE CYCLE CENTER

Modeling recycling in life cycle assessment

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Modeling recycling in life cycle assessment

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Modeling recycling in life cycle assessment

Modellera återvinning i livscykelanalys

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Preface

This project was funded by the Swedish Energy Agency through the Re:Source programme. The project was coordinated within Swedish Life Cycle Center, a national competence center for credible and applied life cycle thinking in industry and society. The project partners contributed to the funding through case studies or other in-kind contributions. Case studies were provided by SSAB, Outokumpu, Essity, Tetra Pak, Volvo, RISE and KTH. All partners contributed to the discussions during the project. Professor Magdalena Svanström at Chalmers Division of Environmental Systems Analysis reviewed the report, which allowed us to improve it on many points. The responsibility for the final version of the report rests with the authors, however. Where views of other participants are presented, they do not represent an official view of their organization but should be interpreted as the opinion of the individual participants.

Content

Summary

Recycling of material from one product to another creates an allocation problem in life cycle assessment (LCA), because the same material is used in at least two different products. The choice of method for modeling material recycling can have a decisive impact on the environmental assessment of products that have a high content of recycled material and products that are recycled after use. This choice has been discussed since the early 90's but no consensus has yet been reached. The recent EU guidelines on Product Environmental Footprint (PEF) includes a rather complex approach: the Circular Footprint Formula (CFF). In response to these guidelines, the Swedish Life Cycle Center gathered companies, researchers and authorities in a project aiming to analyze and discuss how open-loop recycling of materials should be modeled in LCA and similar environmental assessments.

To develop a basis for the analysis and discussion, we compiled information on twelve different methods for modeling open-loop recycling. We also developed a set of criteria for assessing the methods. These parts of the project were both based on literature surveys. The twelve methods were then assessed by LCA researchers, tested in case studies on industrial products, and debated among all project partners.

The literature survey on methods for modeling recycling focusses on important standards and guidelines, but also includes a small selection of scientific papers. The twelve methods found are listed in Figure S.1. They are described in text, illustrations, and equations in in the chapter *Methods for modeling recycling*. This chapter also discusses the methods in terms of, for example, how easy they are to apply, what incentives they give for recycling, and whether they fit in attributional LCA or consequential LCA (ALCA or CLCA). An ALCA aims to identify the share of the global activities and their environmental burdens that belong to a product. A CLCA, in contrast, seeks to identify how the global environmental burdens are affected by the production and use of the product investigated.

To facilitate a discussion on what methods fit in ALCA and CLCA, we define and distinguish between two life cycle concepts: product life cycle and material life cycle. Both are defined as a system of activities connected by material and energy flows that are part of the product or service investigated, or part of its production, use or waste management. The activities in the product life cycle range from the production of virgin or secondary material, through manufacturing processes and use, to the waste management of the product, which might generate material for recycling into other products. The material life cycle, in contrast, ranges from the production of virgin material, through (possibly multiple cycles of) manufacturing processes, use, and recycling, until the final waste management of material that is no longer recycled.

A second literature survey serves as basis for the development of criteria for assessing the twelve methods. Our starting point is an earlier set of five criteria: that methods for environmental assessments should ideally 1) be easy to use, 2) generate accurate results that 3) decision-makers can understand and 4) find relevant to their decisions, and 5) be robust enough to resist misuse. These criteria were derived from

the notion that environmental assessments ultimately serve the purpose to reduce environmental impacts or, at least, to reduced environmental impacts per functional unit. After a survey of scientific literature on classification and evaluation of methods for environmental assessments, we disaggregate the five previous criteria into ten different criteria or indicators that can be used to evaluate methods for environmental assessments in general. The criteria and their development are described in the chapter *Criteria for assessing allocation methods* and Annexes 1-2. The assessment of the twelve methods is summarized in Figure S.1 and described in the chapter *Assessment of methods*.

Method / Criteria	A. Easy to use	B. Readily available data	C. Generalizable results	D. Reflects decisive characteristics	E. Life cycle scope	F. Explicit, justified, and evaluated	G. Comprehendible	H. Relevant to decision-makers	I. Legitimate	J. Reproducible
1. Simple cut-off	Green	Green	Green	Red	Green	Green	Green	Green	Yellow	Green
2. Cut-off with economic allocation	Green	Green	Green	Red	Green	Green	Green	Green	Yellow	Yellow
3. Cut-off plus credit	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Green	Green	Green	Red
4. Allocation to material losses	Green	Green	Green	Yellow	Green	Green	Green	Yellow	Yellow	Yellow
5. Allocation to virgin material use	Green	Yellow	Green	Yellow	Green	Red	Green	Yellow	Red	Yellow
6. 50/50 methods	Green	Yellow	Green	Yellow	Green	Green	Green	Green	Green	Yellow
7. Quality-adjusted 50/50 methods	Red	Red	Green	Green	Yellow	Yellow	Red	Green	Green	Yellow
8. Circular Footprint Formula	Red	Yellow	Green	Green	Green	Green	Red	Green	Green	Yellow
9. Market price-based allocation	Yellow	Yellow	Green	Green	Green	Green	Green	Green	Yellow	Yellow
10. Market price-based substitution	Red	Red	Green	Green	Green	Yellow	Red	Green	Green	Red
11. Price-elasticity approaches	Red	Red	Green	Green	Green	Red	Red	Green	Green	Red
12. Allocation at the point of substitution	Red	Red	Green	Yellow	Green	Green	Red	Green	Yellow	Red

Figure S.1: Summary of assessment of the methods applying the ten criteria. Green = criteria fulfilled. Yellow = criteria partly fulfilled. Red = criteria not fulfilled.

The methods for modeling recycling are tested in case studies on hot- and cold-rolled steel, respectively, stainless steel tubes, a metal-powder product, concrete, plastic packaging, and beverage packaging. We also tested them in a case of reuse of batteries from an electric bus. The experience from these tests is summarized in Annexes 3-9 and used as input to the assessment of the methods.

Finally, the pros and cons of the different methods were debated in workshops, focus groups, and an email exchange where all project partners were invited. The discussion was structured in three application areas of LCA results: policy, external communication, and internal use (see the chapter *Debating the methods*), because we expected the requirements on the methods to differ between these arenas.

The methods discussed in this study differ not only in how they deal with the allocation problem at open-loop recycling, but also in how the allocation problem is defined. With the Simple and Economic cut-off methods, the challenge is just to decide how to allocate the recycling process. This implies that the allocation problem only includes the recycling process. Most other methods include virgin material production in the allocation method, although in different ways. When Price-based allocation or Allocation at the point of substitution (APOS) is applied, part of the virgin production of any recycled material in the product is allocated to the product. The methods Cut-off plus credit, Quality-adjusted 50/50, CFF, and Price-based substitution instead account for part of the virgin production avoided through recycling after use in the product. Allocation to material losses or to virgin material use, the 50/50 methods and the price-elasticity methods, can include either allocation of the actual virgin production of the material, or the virgin material production avoided through recycling. These four methods and Price-based substitution in addition includes the final waste management of the material in the allocation problem. The APOS approach considers recycled material a by-product of the life cycle where it is generated, which means it requires part of the whole product life cycle to be allocated to the recycled material.

The Simple and Economic cut-off methods fit easily in an ALCA, because they include nothing but the product life cycle. We argue that an ALCA can also include allocated parts of the virgin material of recycled material and/or the final waste management of material recycled from the product. Although these processes are not part of the product life cycle, they are clearly part of the material life cycle.

Virgin material production and waste disposal avoided through recycling are not part of any life cycle and, hence, do not fit with the aim of ALCA to identify the share of actual activities that belongs to a product. Approaches that include avoided activities fit better in CLCA, which aims to estimate the consequences of producing and using the product. Further analysis is required to decide which method for modeling recycling most accurately reflect the foreseeable consequences of using or supplying recyclable materials.

Note that Allocation to material losses, Allocation to virgin material use, the 50/50 methods and the price elasticity methods can be adapted to fit in either ALCA or CLCA, depending on whether the virgin material production and final disposal are the actual processes in the material life cycle, or the activities avoided through recycling.

The level of complexity of the methods ranges from low for Simple cut-off to high for several methods with a complexity comparable to the CFF (see Figure S.1). The PEF guidelines includes default data on some of the factors of the CFF. This makes CFF more feasible to apply, compared to the other complex methods.

The methods also vary in the incentives they give to decision-makers. Allocation to material losses typically gives a strong incentive to design for recycling, and to collection for recycling of waste. Allocation to virgin material use is instead likely to give a strong incentive to the use of recycled material. Cut-off methods in many cases also give this incentive. Other methods can give an incentive both to using recycled material and to recycle material after use, and also to preserving the quality or economic value of the material; however, these incentives are weaker and less significant compared to the more extreme methods Allocation to material losses or to virgin material use.

The debate among project partners made clear that the requirements on methods vary between the application areas policy, external communication, and internal use. In an LCA for internal use, it might be relevant to account for risks and benefits that are not certain enough to be communicated externally. Internal use of LCA in, for example, product development might call for the use of simplified methods, even if these do not meet the quality requirements of LCAs for external use.

However, the debate also highlighted overlaps between the application areas. Methods used by companies to generate results for external communication are also relevant for internal use, to inspire improvements that companies can benefit from in their external communication. Environmental Product Declarations and their associated methods are useful for the policy instrument green procurement, but also for external business-to-business communication.

We also found that the requirements on methods can vary within each application area. When the LCA results are used as part of the basis for policy decisions or strategic decisions in companies, the main purpose of the LCA is to generate relevant knowledge. The same can hold when the LCA is produced by a company to educate key external actors. In these applications (colored red in Table S.1), it is useful to regard LCA as a learning process rather than a calculation tool. This suggests that the methods should be tailor-made to make the learning process efficient and generate as much knowledge as possible in the specific case study.

In other applications, the main purpose of the LCA is to generate numerical results. This means the LCA is mainly a calculation tool. The requirements on this tool will vary between applications. If the LCA is made within the framework of environmental labelling, green procurement or to make environmental assertions to authorities or customers, the methods should be robust and well-defined in advance to make the results from different LCAs comparable (blue color in Table S.1). If the LCAs are made to support day-to-day decisions in, for example, product development, it must be possible to apply the methods quickly (yellow in Table S.1).

Since different requirements are important depending on the application of the LCA, it is unlikely that a single method for modeling recycling is adequate for all applications.

Table S.1: Requirements on the method vary with the application. Red color indicates that the main requirement is to generate relevant knowledge. Blue indicates that the method must be robust and generate reproducible results. Yellow indicates that the main criterion is the ease of use.

Application area	LCA used as learning process with tailor-made method(s)	LCA used as a calculation tool with predefined method
Policy-making	Develop basis for policy-decision	Required by a policy instrument
External communication	General communication on product and its environmental performance	Environmental Product Declarations, etc.
Internal use	Develop basis for strategic decisions	Day-to-day decisions

Sammanfattning

Vid open-loop-återvinning, där material från en produkt återvinns till en annan produkt, uppstår ett så kallat allokeringsproblem i en livscykelanalys (LCA). Det beror på att samma material används i minst två olika produkter, och en LCA brukar kvantifiera miljöpåverkan för en enda produkt. Valet av metod för modellering av materialåtervinning kan ha en avgörande inverkan på miljöbedömningen av produkter som har ett högt innehåll av återvunnet material och produkter som återvinns efter användning. Detta metodval har diskuterats sedan början av 90-talet, men ingen konsensus har ännu uppnåtts. EU:s senaste riktlinjer för produktmiljöavtryck (PEF) innehåller en ganska komplicerad metod: Circular Footprint Formula (CFF). Med anledning av detta sammanförde Swedish Life Cycle Center företag, forskare och myndigheter i ett projekt som syftar till att analysera och diskutera hur ”open loop”-återvinning av material ska modelleras i LCA och liknande miljöbedömningar.

Som underlag för analysen och diskussionen sammanställde vi information om tolv olika metoder för modellering av ”open loop”-återvinning. Vi utvecklade också en uppsättning kriterier för utvärdering av metoderna. Dessa delar av projektet baserades på litteratursökningar. De tolv metoderna utvärderades sedan av LCA-forskare, testades i fallstudier av industriprodukter och diskuterades av alla projektpartners.

Litteraturundersökningen om metoder för modellering av återvinning fokuserar på viktiga standarder och riktlinjer, men omfattar också ett litet urval av vetenskapliga artiklar. Figur S.1 visar de tolv metoder som valdes ut. Metoderna beskrivs i text, illustrationer och ekvationer i rapporten. Texten inkluderar en diskussion av, exempelvis, hur enkla metoderna är att tillämpa, vilka incitament de ger för återvinning och om de passar in i en bokföring-LCA (attributional LCA; ALCA) eller i en konsekvens-LCA (consequential LCA; CLCA). Dessa typer av LCA har olika syften: en ALCA syftar till att identifiera vilken andel av de global mänskliga aktiviteterna och deras miljöbelastningar som tillkommer en produkt; en CLCA försöker däremot identifiera hur den globala miljöbördan påverkas av produktionen och användningen av den undersökta produkten.

För att underlätta en diskussion om vilka metoder som passar i ALCA respektive CLCA, definierar och skiljer vi mellan två livscykelbegrepp: produktlivscykel och materiallivscykel. Båda definieras som system av aktiviteter kopplade till material- och energiflöden som är en del av den undersökta produkten eller tjänsten, eller en del av dess produktion, användning eller avfallshantering. Produktlivscykeln sträcker sig från produktion av jungfruligt eller sekundärt material, genom tillverkningsprocesser och användning, till avfallshantering av produkten, som kan generera material för återvinning till andra produkter. Materiallivscykeln sträcker sig från produktionen av jungfruligt material, genom (eventuellt flera cykler av) tillverkningsprocesser, användning och återvinning till slutlig hantering av avfall av material som inte längre återvinns.

I utvecklingen av kriterier för bedömning av de tolv metoderna utgår vi ifrån en tidigare uppsättning av fem kriterier för utvärdering av metoder för miljöbedömningar: att de helst bör 1) vara enkla att använda, 2) generera korrekta resultat som 3) beslutsfattare kan förstå och 4) uppleva som relevanta för sina beslut och dessutom 5) vara tillräckligt robust för att motstå missbruk. Dessa kriterier härleddes från utgångspunkten att syftet med miljöbedömningar är att minska miljöpåverkan, eller åtminstone leda till minskad miljöpåverkan per funktionell enhet. Efter en undersökning av vetenskaplig litteratur om klassificering och utvärdering av metoder för miljöbedömningar, utvecklar vi i detta projekt tio mer detaljerade kriterier eller indikatorer som kan användas för att utvärdera metoder för miljöbedömningar. De tolv metoderna, tio kriterierna och resultaten av utvärderingen av metoderna sammanfattas i figur S.1.

Method / Criteria	A. Enkel metod	B. Lättillgängliga data	C. Generaliserbara resultat	D. Avspeglar viktiga aspekter	E. Livscykelperspektiv	F. Dokumenterad, motiverad, utvärderad	G. Begriplig	H. Relevant för beslutsfattare	I. Legitim	J. Reproducerbar
Enkel cut-off	🙂	🙂	🙂	☹️	🙂	🙂	🙂	🙂	😐	🙂
Cut-off med ekonomisk allokering	🙂	🙂	🙂	☹️	🙂	🙂	🙂	🙂	😐	😐
Cut-off plus kredit	😐	😐	☹️	😐	😐	😐	🙂	🙂	🙂	☹️
Allokering till materialförluster	🙂	🙂	🙂	😐	🙂	🙂	🙂	😐	😐	😐
Allokering till jungfruligt material	🙂	😐	🙂	😐	🙂	☹️	🙂	😐	☹️	😐
50/50-metoder	🙂	😐	🙂	😐	🙂	🙂	🙂	🙂	🙂	😐
Kvalitetsjusterade 50/50-metoder	☹️	☹️	🙂	🙂	😐	😐	☹️	🙂	🙂	😐
Circular Footprint Formula	☹️	😐	🙂	🙂	🙂	🙂	☹️	🙂	🙂	😐
Prisbaserad allokering	😐	😐	🙂	🙂	🙂	🙂	🙂	🙂	😐	😐
Prisbaserad substitution	☹️	☹️	🙂	🙂	🙂	😐	☹️	🙂	🙂	☹️
Priselasticitets-metoder	☹️	☹️	🙂	🙂	🙂	☹️	☹️	🙂	🙂	☹️
Allokering vid subsitutionspunkten	☹️	☹️	🙂	😐	🙂	🙂	☹️	🙂	😐	☹️

Figur S.1: Sammanfattning av utvärderingen av metoderna. Grönt = kriteriet uppfyllt. Gult = kriteriet delvis uppfyllt. Rött = kriteriet inte uppfyllt.

Vi testar även metoderna för modellering av återvinning i flera fallstudier: på varm- respektive kallvalsat stål, rostfritt stålrör, en metallpulverprodukt, betong, plastförpackning och dryckesförpackning. Ytterligare en fallstudie gäller återanvändning av batterier från en elbuss. Erfarenheter från dessa fallstudier används som underlag till en reviderad utvärdering av metoderna.

Slutligen diskuterar vi metodernas för- och nackdelar i workshops, fokusgrupper och med hjälp av e-post, där alla projektpartners kan delta. Diskussionen struktureras i tre tillämpningsområden för LCA-resultat: policy, extern kommunikation och intern användning (se kapitel 5), eftersom vi förväntade oss att kraven på metoderna skulle skilja sig mellan dessa arenor.

Metoderna som diskuteras i denna studie representerar olika synsätt, inte bara i hur allokeringsproblemet ska hanteras utan även i vad problemet är. När enkel cut-off eller cut-off med ekonomisk allokering används, är problemet bara att bestämma om själva återvinningsprocessen ska räknas till den ena eller andra produktlivscykeln, eller fördelas mellan dem på något sätt. Med andra ord inkluderar allokeringsproblemet bara återvinningsprocessen. De flesta andra metoder inkluderar produktionen av jungfruligt material i allokeringsproblemet, om än på olika sätt. När prisbaserad allokering eller allokering vid substitutionspunkten (APOS) tillämpas, tillskrivs den studerade produkten en del av den jungfruliga produktionen av den återvunna material som ingår i produkten. Med cut-off plus kredit, kvalitetsjusterade 50/50-metoder, Circular Footprint Formula (CFF) och prisbaserad substitution inkluderar LCAn istället en del av den jungfruliga produktion som undviks genom återvinning av materialet. Allokering till materiella förluster eller till jungfruligt material, 50/50-metoder och prismässig metod är flexibla på så sätt att de kan inkludera antingen allokering av den faktiska jungfruliga produktionen av materialet eller den produktion av jungfruligt material som undviks genom återvinning. Dessa fyra metoder och prisbaserad substitution inkluderar dessutom den slutliga avfallshanteringen av materialet i allokeringsproblemet. APOS-metoden behandlar det återvunna materialet som en biprodukt från den produktlivscykel där det genereras, vilket innebär att hela den livscykeln ingår i allokeringsproblemet.

Enkel cut-off och cut-off med ekonomisk allokering passar bra i en ALCA, eftersom de bara innehåller produktlivscykeln. Vi menar dock att en ALCA också kan inkludera en del av den jungfruliga produktionen av det återvunna materialet i produkten och/eller den slutliga avfallshanteringen av material som återvinns från produkten. Dessa processer ingår inte i produktens livscykel, men är en del av materialets livscykel.

Den produktion av jungfruligt material och avfallshantering som undviks genom återvinning är inte en del av någon livscykel och hör därför inte hemma i en ALCA, vars mål att identifiera de faktiska aktiviteter som tillhör en produkt. Metoder som inkluderar undvikna aktiviteter i LCAn passar bättre i en CLCA, som syftar till att uppskatta konsekvenserna av att producera och använda produkten. Ytterligare analys krävs för att avgöra vilken metod för modellering av återvinning som mest korrekt återspeglar de förutsebara konsekvenserna av att använda eller leverera återvinningsbara material.

Observera att allokering till materialförluster eller till jungfruligt material, metoderna 50/50-metoderna och priselasticitets-metoderna kan anpassas för att passa in i antingen ALCA eller CLCA, beroende på om produktionen av jungfruligt material och avfallshantering är de faktiska processerna i materialets livscykel eller de aktiviteter som undviks genom återvinning.

Metodernas komplexitet varierar från enkel cut-off till flera metoder som är ungefär lika komplexa som CFF (se figur S.1). Inom PEF finns default-data för några av faktorerna i CFF. Detta gör CFF lättare att tillämpa jämfört med andra komplexa metoder.

Metoderna varierar också i de incitament de ger till beslutsfattare. Allokering till materialförluster ger normalt starka incitament till att utveckla produkter som lätt kan återvinnas och till att samla in avfall till återvinning. Allokering till jungfruligt material ger istället ett starkt incitament för användning av återvunnet material. Cut-off-metoder ger i många fall också det incitamentet. Andra metoder kan ge incitament både till att använda återvunnet material och att återvinna material efter användning, och kan dessutom ge incitament till att bevara materialets kvalitet eller ekonomiska värde; dessa incitament är dock svagare och mindre signifikanta jämfört med de mer extrema metoderna allokering till materialförluster eller allokering till jungfruligt material.

Diskussioner bland projektets deltagare gjorde klart att kraven på metoder kan variera inom de olika tillämpningsområdena policy, extern kommunikation och intern användning. I en LCA för internt bruk kan det vara relevant att redovisa miljörisker och -vinster som är för osäkra för att kommuniceras externt. Intern användning av LCA i exempelvis produktutveckling kan kräva användning av förenklade metoder, även om dessa inte uppfyller krav på kvalitet som ställs på LCA för extern användning.

Debatten belyste dock även överlapp mellan tillämpningsområdena. Metoder som används av företag för att generera resultat för extern kommunikation är också relevanta för intern användning, för att LCA-resultaten ska styra mot förbättringar som företaget kan dra nytta av i sin externa kommunikation. Miljövarudeklarationer och liknande metoder är användbara i styrmedlet grön upphandling, men också för extern kommunikation mellan företag.

Vi fann också att kraven på metoder kan variera inom varje tillämpningsområde. När LCA-resultat används som underlag i policyutveckling eller strategiska beslut i företag är LCA-studiens huvudsakliga syfte att generera relevant kunskap. Detsamma kan vara fallet när en LCA tas fram av ett företag för att informera externa aktörer. I dessa tillämpningar (rödfärgade i tabell S.1) är LCA en lärprocess snarare än ett beräkningsverktyg. Metoderna bör då skräddarsys för att göra lärprocessen effektiv och generera så mycket kunskap som möjligt i den specifika fallstudien.

I andra tillämpningar kan huvudsyftet med LCA vara att generera numeriska resultat. Detta betyder att LCA i huvudsak är ett beräkningsverktyg. Kraven på detta verktyg varierar mellan tillämpningsområden. Om LCA görs inom ramen för miljömärkning, grön upphandling eller för att göra miljömässiga påståenden till myndigheter eller kunder, behöver metoderna vara robusta och väl definierade i förväg. På så sätt blir resultaten från olika LCA-studier jämförbara (blå färg i tabell S. 1). Om LCA-studien istället görs för att stödja dagliga beslut i en verksamhet, till exempel som stöd för produktutvecklare, måste metoderna vara snabba och lätta att använda (gult i tabell S.1).

Eftersom olika krav är viktiga beroende på tillämpningen av LCA, är det osannolikt att en enda metod för modellering av återvinning passar för alla tillämpningar.

Tabell S.1: Kraven på metoden varierar beroende på syftet med LCAn. Röd färg indikerar att huvudkravet är att generera relevant kunskap. Blått indikerar att metoden måste vara robust och generera reproducerbara resultat. Gult indikerar att huvudkriteriet är metoden är lätt att använda.

Användningsområde	LCA är en lärprocess med skräddarsydda metoder	LCA är ett beräkningsverktyg med fördefinierad metod
Policy	Ta fram underlag till styrmedel och annan policyutveckling	Uppfylla krav i styrmedel
Extern kommunikation	Allmän kommunikation om produkten och dess miljöprestanda	Miljövarudeklaration, etc.
Intern användning	Ta fram underlag för strategiska beslut	Dagliga beslut i verksamheten

Abbreviations and key concepts

APOS	Allocation at the point of substitution
Attributional LCA (ALCA)	An LCA that aims to identify the share of the global activities and their environmental burdens that belong to a product system.
Consequential LCA (CLCA)	An LCA that aims to estimate how the global environmental burdens are affected by the production and use of the product investigated.
CEN	European Committee for Standardization
EC	European Commission
EPD	Environmental Product Declaration
EU	European Union
ISO	International Organization of Standardization
KTH	Royal Institute of Technology, the university of technology in Stockholm
LCA	Life-cycle assessment
Material life cycle	A system of activities connected by material and energy flows that are part of the product or service investigated, or part of its production, use or waste management. The activities range from the production of virgin material, through (possibly multiple cycles of) manufacturing processes, use, and recycling, until the final waste management of material that is no longer recycled.
PEF	Product Environmental Footprint
Product life cycle	A system of activities connected by material and energy flows that are part of the product or service investigated, or part of its production, use or waste management. The activities range from the production of virgin or secondary material, through manufacturing processes and use, to the waste management of the product, which might generate material for recycling into other product life cycles.
UBA	Umweltbundesamt, Germany's central environmental authority

Introduction

Background

Material recycling reduces the need for primary production of materials, as well as for waste treatment (energy recovery and disposal) of used materials. This typically results in an environmental benefit. In open-loop recycling, the material is recycled from one product into another. In life cycle assessment (LCA), which aims to quantify the environmental impacts of a single product, this poses a challenge.

Two main approaches to LCA exist, which correspond to two different purposes of the LCA (see Weidema 2003, Brandão et al. 2017, Ekvall 2019). A consequential LCA (CLCA) seeks to identify how the global environmental burdens are affected by the production and use of the product investigated. For open-loop recycling, this requires an analysis or assumption of to what extent the virgin production and waste management of different materials are avoided through the use of recycled materials in the product and by the recycling of the product after use. Based on this analysis or assumption, the system investigated is expanded to include the avoided processes. The challenge is to decide on what part of the avoided processes is a consequence of the use of recycled materials, and what part is a consequence of material recycling after use.

An attributional LCA (ALCA), in contrast, aims to identify the share of the global activities and their environmental burdens that belong to a product system. For open-loop recycling, this implies a decision on how the environmental impact of the actual primary production, the recycling processes and the final waste management should be allocated between the various products where the material is used. Avoided processes do not come into this equation. On the contrary, negative numbers that represent avoided emissions would muddle the estimate of the share of the global emissions that belong to the product system investigated in the ALCA.

It is apparent from the above that the modeling of material recycling in LCA can involve much more than the recycling process; the modeling of initial or avoided primary production and final or avoided waste management is often at least as important for the results of the study.

Many scientific articles and dissertations with various proposals on how to model recycling in LCA have been published since the early 1990s (e.g., Boguski et al. 1994, Ekvall 2000, Allacker et al. 2017, Schrijvers 2017).

An international standard for LCA was published in 1997 and revised in 2006 (ISO 2006). The recommendations in this standard can be interpreted in various ways, although a technical report (ISO 2012) helps guiding this interpretation. The standard is currently being refined with a focus, among other things, on how the allocation problems should be managed.

In 2008, the European Union (EU) initiated a process that involved many researchers, companies and authorities to develop new guidelines for a kind of LCA called Product Environmental Footprint (PEF) and Organisation Environmental

Footprint. These guidelines include a specific method for modeling of recycling: the Circular Footprint Formula (CFF). The CFF accounts for many aspects of recycling (type of material, quality losses, etc.) and is therefore relatively complicated (Zampori et al. 2016). This makes it difficult to explain and to understand the approach. It might also be difficult to apply the CFF in practice if, for example, the recycled product is complex and includes many materials. All aspects of the PEF methodology have not yet been defined. It has also not yet been decided when and to what extent the PEF guidelines will be used.

Other international standards and guidelines also give specific recommendations on (e.g., EC 2010, BSI 2011, WRI & WBCSD 2011, CEN 2012, ISO 2018a). These recommendations contradict each other, at least in part.

Past and current efforts on harmonizing and standardizing the method for modeling material recycling in LCA indicate it is difficult to reach consensus. This is not surprising, because various methods can be defended, depending on perspective and criteria for what is a good method (Ekvall & Tillman 1997). Different recycling modeling methods are applicable in ALCA and CLCA. Different methods might also be valid depending on where and for what purpose the LCA is carried out.

In the scientific literature and published guidelines, methods for modeling recycling are regrettably often recommended without clear arguments or explicit criteria for what is a good method. Ekvall et al. (2004) and Ekvall (2018 and 2020) present a system of criteria for methods in environmental systems analysis based on the notion that a method is better the more it can be expected to contribute to reducing the negative environmental impacts of humanity or, at least, the impact per unit of produced benefit. This implies that a good method must be feasible to apply and preferably be easy to use. The results need to be reasonably accurate, possible to understand and communicate, and be considered relevant to decision-makers. Moreover, the method should not be easy to use to defend decisions that are bad for the environment.

No method is likely to fully meet all the above criteria. There is, for example, likely to be a trade-off between accuracy and ease of communication: a complex method such as the CFF can account for many relevant aspects of recycling, but a high level of complexity also makes the method more difficult to communicate. Hence, this set of criteria is not sufficient to identify a method as superior to all other methods. Instead, it is a tool to structure the debate over pros and cons of different methods.

Purpose

This project aims to describe and assess different approaches to modeling recycling in LCA and similar environmental assessments. It strives to facilitate a debate among Swedish actors on how recycling should be modelled in LCA and similar assessments. It also aims at contributing to international harmonization and standardization processes. The project gives Swedish companies, researchers and authorities an opportunity to influence and contribute to the international development in the field, aiming at improving incentives for recycling, and also at improving the basis for policy-making and other decisions that affect the recycling of materials.

We have the following objectives:

- increase the knowledge within Swedish industrial companies and authorities on how recycling should be modelled in environmental assessments such as LCA, according to important international guidelines that already exist or are under development,
- increase the knowledge among companies, authorities and researchers on how these guidelines affect the environmental assessment of products, in particular with regard to products from the participating companies,
- reach consensus among participating researchers, companies and authorities on how recycling should be modelled in environmental assessments, or describe the different views of the participating companies and researchers, and
- contribute to the ongoing debate on methods for modeling recycling, and to the development of PEF and other international harmonization of LCA methodology.

Methods of the project

The project included eight work packages (WPs):

1. Project management: project manager and scientific coordinator was Tomas Ekvall, researcher at IVL Swedish Environmental Research Institute and Adjunct Professor at Chalmers University of Technology. The project was coordinated through Swedish Life Cycle Center by three consecutive project coordinators: Daniela Michael, Jenny Lagergren, and Maria Rydberg.
2. Inventory of methods: literature study to collect and compile information on state-of-the-art and available methods for modeling material recycling in LCA. The literature study focused on important standards and guidelines, but also included a few complementary scientific papers. Information on twelve different methods was drawn from this literature. These were illustrated graphically and with equations. Descriptions of the methods were made with regard to their ease of use, the incentives they give for increasing recycling, and whether they fit in ALCA and/or CLCA.
3. Criteria for assessing the methods: a separate literature study was made with the purpose to assess and refine the criteria for good methods presented by Ekvall (2018 and 2020). The outcome was a set of ten less aggregated criteria or indicators for evaluating methods for environmental assessments in general and methods for modeling recycling in particular.
4. Assessment of methods: the 12 methods for modeling recycling were assessed based on the 10 criteria defined in WP 3. To make the large number of assessments ($12 \times 10 = 120$) feasible to make and possible to communicate,

they are reported with color-coded smileys (e.g., happy green smiley = criteria fulfilled) and short comments, only.

5. Case studies: the methods were tested in case studies of hot- and cold-rolled steel, stainless steel tubes, a metal-powder product, concrete, plastic packaging, and beverage packaging. We also tested the method in a case of reuse: the reuse of batteries from an electric bus. Most case studies were performed in the industry producing the product, but the studies on a metal-powder product, concrete, and bus batteries were carried out at a research institute or a university. A calculation sheet in Excel was produced to facilitate the use of all modelling methods in the case studies. This calculation sheet included the formulas of all methods and also default data to be used when specific data were missing.

6. Update of the assessment: the criteria defined in WP 3 and the assessment of methods in WP 4 were revised based on the findings from the case studies in WP5 and on feedback from the partners.

7. Consensus process: we investigated to which extent consensus can be reached on the modeling methods among the many project partners. The consensus procedure started with a World Café workshop, after which three focus groups were initiated to discuss methods applicable in policy, external communication and internal industrial use, respectively. The resulting text was commented and discussed in several rounds.

8. Dissemination of results: several project partners were active in the Swedish working group providing input to the amendment of ISO 14044: IVL Swedish Environmental Research Institute, Royal Institute of Technology (KTH), Chalmers University of Technology, Essity, Tetra Pak and Jernkontoret. IVL and Essity were also active in the PEF process during the project. Partial results from the project were disseminated to researchers and industry at an international Life Cycle Management conference (Ekvall et al. 2019), through Swedish seminars, and with a book chapter (Ekvall & Brandão 2020). The final results are presented in this report. A summary of the results was also presented at a webinar organized by Swedish Life Cycle Center.

The report

This report is a joint product from all partners in the project. However, specific researchers were responsible for different parts. The second chapter, *Methods for modeling recycling*, describes the methods for modeling material recycling in LCA. It is based on the inventory of methods (WP 2) conducted by prof. Ekvall with feedback from other project partners. The third chapter, *Criteria for assessing allocation methods,* presents the discussion on criteria and the final criteria used for assessing the methods (WPs 3 and 6). This chapter was produced by Anna Björklund, Associate Professor at KTH, after a dialogue with prof. Ekvall and with feedback from other project partners. The fourth chapter, *Assessment of methods,* presents the final assessment of the methods (WPs 4 and 6) made by Kristian Jelse and Gustav Sandin, both researchers at IVL, with input from prof. Björklund and prof. Ekvall and with feedback from other partners. The fifth chapter, *Debating the methods,* includes the results from the consensus process with all partners (WP 7), compiled and edited by prof. Ekvall. The final chapter, *Conclusions, utilization, and steps forward* was written by prof. Ekvall with feedback from other partners. Annexes 1-2 were written by prof. Björklund and resulted from the literature study on criteria for assessing methods (WP 3). The case studies (WP 5) are briefly summarized in:

- Annex 3 by Pernilla Cederstrand at Essity,
- Annex 4 by Jonas Larsson at SSAB assisted by Gustav Sandin at IVL,
- Annex 5 by Camilla Kaplin at Outokumpu,
- Annex 6 by Lars Winborg and Erika Kloow at Tetra Pak,
- Annex 7 by Patrik William-Olsson and Mats Zackrisson at RISE,
- Annex 8 by Seyed Salehi, master student at KTH supervised by prof. Björklund, and
- Annex 9 by Anton Jacobson and Mia Romare at IVL on behalf of Volvo.

Methods for modeling recycling

This chapter describes many of the methods that have been suggested for modeling of recycling in LCA (see Table 1). As indicated above, we include all methods stipulated by important standards and guidelines. To make the study more comprehensive, we also include a few methods recommended or described in scientific papers known to us in advance. This part of the literature study did not, however, include the full scientific literature on the topic. We also did not include all methods covered by previous surveys (Ekvall & Tillman 1997, Allacker et al. 2017), but only methods necessary for our analysis and discussion.

Table 1: Methods described in this report.

Method	Alternative names	Recommended by
Simple cut-off	Recycled content approach 100/0 method	International EPD system PAS 2050 Greenhouse Gas Protocol
Cut-off with economic allocation	-	Dutch Handbook on LCA
Cut-off plus credit	Module D	ISO 21930:2017 EN 15804:2012+A2 + CEN/TR 16970:2016 EN16485:2014
Allocation to material losses	Closed-loop approximation 0/100 method End-of-life approach Recyclability substitution Value of scrap approach	ISO 14044:2006 + ISO TR 14049:2012 ISO 14067:2018 ISO 20915:2018 PAS 2050:2011 Greenhouse Gas Protocol WorldSteel Association International Stainless-Steel Forum
Allocation to virgin material use	100/0 method	-
50/50 methods	-	Nordic Guidelines on LCA Ekvall (2000)
Quality-adjusted 50/50 methods	UBA approach	German requirements on LCA of beverage packaging Allacker et al. (2017)
Circular Footprint Formula	PEF approach	Product Environmental Footprint Guide
Market price-based allocation	Open-loop procedure	ISO 14067:2018
Market price-based substitution	-	Schrijvers et al. (2016a)
Price-elasticity approaches	Market-based modeling	Ekvall (2000)
Allocation at the point of substitution	APOS	Ecoinvent

The chapter includes a graphical illustration of each method, using a hypothetical case where a material is used in three products with a recycling process between each of the product life cycles (see Figure 1). The product life cycle is here defined as a system of activities connected by material and energy flows that are part of the product or service, or part of its production, use or waste management. These activities range from the production of virgin or secondary material, through manufacturing processes and use, to the waste management, which might generate material for recycling into other product life cycles. With this definition, the life cycle does not include activities that are avoided due to, for example, recovery of materials or energy in waste-management processes. This means the system investigated in a CLCA is expanded beyond the product life cycle when it accounts for the avoided processes (see Background in the Introduction).

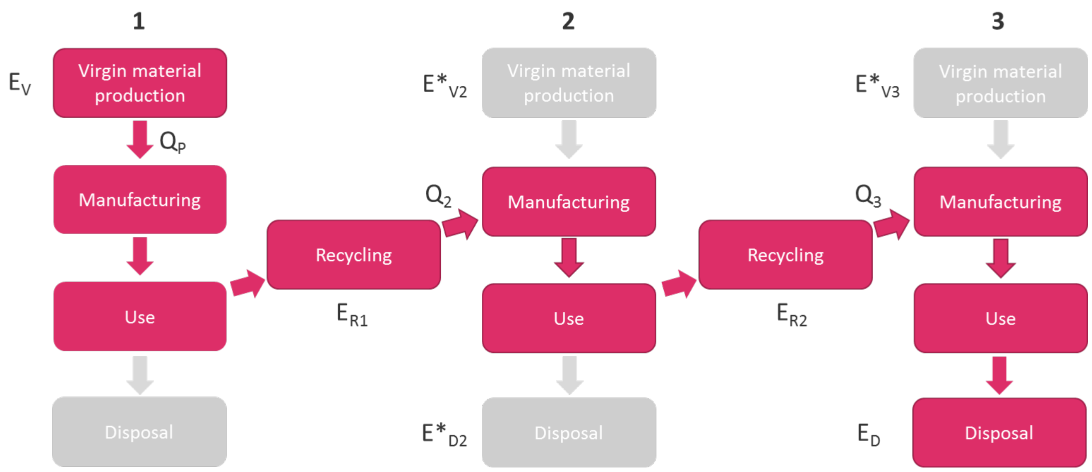

Figure 1: Hypothetical case of a material that through recycling is used in three products. The flow of this material is indicated in pink. Grey indicates processes and flows that are avoided through the recycling and therefore never takes place. The letters are explained in the text below.

In Figure 1, all of the material in Product 1 is recycled into Product 2, which does not include any other material. Similarly, all of the material in Product 2 is recycled into Product 3, which does not include any other material. However, no part of Product 3 is recycled after use.

To further illustrate the methods, we calculate the environmental burdens of virgin material production, recycling and waste disposal for each of the three products using dummy figures:

$E_V = E^*_{V2} = E^*_{V3} = 12$
$E_{R1} = E_{R2} = 4$
$E^*_{D1} = E^*_{D2} = E_D = 6$
$E_{Tot} = E_V + E_{R1} + E_{R2} + E_D$
$Q_P = 1$
$Q_2 = 0.75$ (if not otherwise stated)
$Q_3 = 0.5$ (if not otherwise stated)

where:

- E_V is the environmental burdens of virgin material production,
- E_R is the environmental burdens of the recycling process,
- E_D is the environmental burdens of the waste disposal,
- the asterisk indicates that the process is avoided through recycling,
- E_{Tot} is the total burdens of virgin material production, recycling and disposal in the recycling cascade,
- Q_P is the quality of the material delivered by the primary production,
- Q_2 is the quality of the material delivered by the first recycling process, and
- Q_3 is the quality of the material delivered by the second recycling process.

We present the dummy figures without units to highlight that they are no more than dummy figures used to illustrate the mechanisms of the different methods. In a real case, the environmental burdens could be quantified in terms of emissions (e.g., kg CO_2 per kg material), impacts (e.g., kg CO_2 equivalents per kg material), or aggregated burdens (e.g., Environmental Load Units (ELU) per kg material).

Simple cut-off

The easiest approach to model recycling is probably the cut-off methods. They imply that each product is assigned the environmental burdens of the processes in the life cycle of that product. The only challenge is to define the boundary between the life cycles: should this boundary be before, within, or after the recycling of the material?

A simple cut-off method is recommended by the international system for Environmental Product Declarations (EPD), which defines the boundary between the life cycles as the point where the material has its lowest market value (EPD International 2017, p.60). This is typically before the waste material is collected for recycling (Figure 2). The General Programme Instructions in the International EPD System (one of several existing EPD systems) also specify that the recycling processes should be included in the EPD of the product where the recycled material is used (EPD International 2017, p.62).

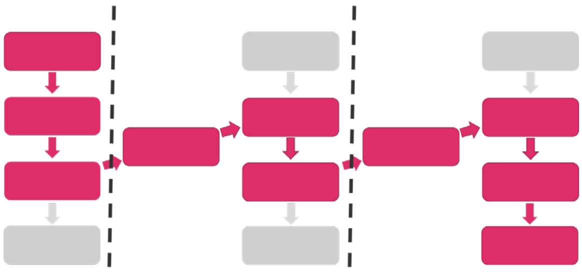

Figure 2: The simple cut-off approach as specified in the International EPD System.

With this method the environmental burdens (E) of virgin material production, recycling and waste disposal for any product (i.e., not just the three products in our hypothetical case) is calculated according to the following equation:

$$E = (1 - R_1) \times E_V + R_1 \times E_R + (1 - R_2) \times E_D$$

where:

- R_1 is the share of recycled material in the product,
- R_2 is the rate of recycling of material after use in the product, and
- E_R is the environmental burdens of the recycling activities that supply recycled material to the product.

Figure 3 shows the results when the method is applied to the hypothetical case in Figure 1, where E_1, E_2 and E_3 are the environmental burdens of Products 1, 2 and 3, respectively.

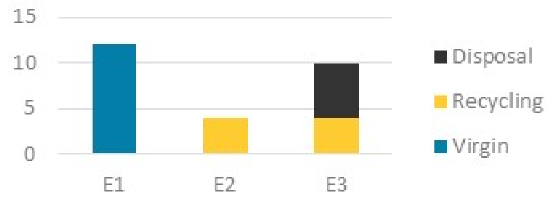

Figure 3: Results from the simple cut-off method applied in our hypothetical case.

This cut-off method means the LCA includes no process beyond the product life cycle. This fits well in an ALCA, which aims to identify the share of the global activities and their environmental burdens that belong to the product system (see Background in the Introduction).

The method gives incentives to use recycled material as long as the recycling has less environmental impact than the virgin materials production ($E_V > E_R$).

The simple cut-off also gives an incentive to recycle a product after use, when the final disposal has a negative net impact on the environment ($E_D > 0$). However, the incentive to recycle is weak when E_D is low. This can be the case even when the actual environmental gain of recycling ($E_V + E_D – E_R$) is high. The bulk metals steel, aluminum and copper are examples of materials where E_D is much lower than the total environmental benefit of recycling ($E_V + E_D – E_R$).

For biogenic materials such as paper, the waste disposal can even have a net positive impact on the environment ($E_D < 0$). This can be the case if the disposal is, for example, incineration with energy recovery of paper and other biogenic materials. In these cases, the simple cut-off gives an incentive not to recycle the biogenic material, even if recycling is good for the environment ($E_V + E_D – E_R > 0$).

Hence, a drawback of the simple cut-off is that it does not give incentives for recycling after use, when the final disposal has little or positive net environmental burdens. This can be the case, for example with wastepaper incinerated after use or with waste polyethene disposed at a landfill.

The simple cut-off method is often called the recycled-content approach (e.g., BSI 2011, WRI & WBCSD 2011, van der Horst et al. 2016). The British Standard for carbon footprint (PAS 2050) recommends the method for cases where the recycled material does not maintain the same inherent properties as the virgin material input (BSI 2011, p.31). The Greenhouse Gas (GHG) Protocol of the World Resources

Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) recommends the method when (WRI & WBCSD 2011, p.74):

- the product investigated contains recycled input, but there is no or an unknown amount of recycling after use,
- the supply of recyclable material exceeds the demand for recycled material, or
- the company doing the LCA has control over how much recycled material to use.

In many of these cases, the GHG Protocol recommends the use of two methods in parallel to assess the robustness of the results: the recycled-content approach and the closed-loop approximation (see below).

The method is also sometimes called the 100/0 method (e.g., Allacker et al. 2017), because 100% of the virgin material production is allocated to the product using virgin material.

Cut-off with economic allocation

The Dutch Handbook on LCA (Guinée et al. 2002) advocates economic allocation. In a subsequent paper Guinée et al. (2004) describe how economic allocation can be applied in, for example, a cut-off approach for recycling of materials. They assume discarded products have a negative economic value and define the boundary between the life cycle to be the point at which the market value of the waste rises to zero.

The value of the waste can turn from negative to positive within a unit process, for example the dismantling of the used product. If so, the dismantling receives revenues from both ends: from accepting the product to be dismantled and from supplying materials for further processing. The economic allocation in this case means that the environmental burdens of the dismantling process is attributed to the upstream and downstream products in proportion to the extent to which they contribute to the revenues of the dismantling process.

The shares allocated upstream and downstream are denoted α and β, respectively (Guinée et al. 2004). This, by definition, means that α=1-β. If the recycling is treated as a single unit process, the environmental burdens of virgin material production, recycling and waste disposal for any product is calculated according to the following equation:

$$E = (1 - R_1) \times E_V + \beta \times R_1 \times E_{Rin} + (1 - R_2) \times E_D + \alpha \times R_2 \times E_{Rout}$$

where:

- E_{Rin} is the environmental burdens of the recycling process supplying recycled material to the product and
- E_{Rout} is the environmental burdens of the recycling process accepting materials from the product.

Figure 4 illustrates the system boundaries in our hypothetical case, if $\alpha = 25\%$ and $\beta = 75\%$. The results obtained with our dummy figures are illustrated by Figure 5.

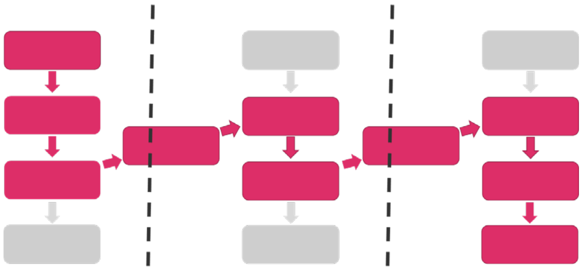

Figure 4: The cut-off with economic allocation of the recycling process, assuming the allocation factors to be $\alpha = 25\%$ and $\beta = 75\%$.

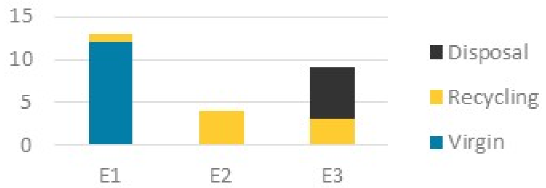

Figure 5: Results from the economic cut-off method applied in our hypothetical case, assuming the allocation factors to be $\alpha = 25\%$ and $\beta = 75\%$.

This cut-off approach fits well in an ALCA because it includes only processes in the life cycle of the product investigated. It gives incentives to use recycled material except when the recycling has much more environmental impact than the virgin materials production ($\beta \times E_{Rin} > E_V$).

The economic cut-off gives incentives to recycle a product after use only when the final disposal has a negative impact on the environment that is greater than the impacts of recycling that are allocated upstream ($E_D > \alpha \times E_{Rout}$). When the waste disposal has a net positive impact on the environment ($E_D < 0$), or only a small negative impact, the economic cut-off gives no incentive to recycle a material after use, even when recycling is actually good for the environment ($E_V + E_D - E_R > 0$). This can be the case for, e.g., metals and glass.

This method is somewhat more complex to apply compared to the simple cut-off method above, because economic allocation means that data on prices must be collected or estimated. However, the method requires no environmental data on processes beyond the product life cycle.

Cut-off plus credit

The European standard for EPDs of construction products in general (EN 15804:2012+A2; CEN 2019), the corresponding international standard (ISO 21930:2017; ISO 2017) and the European standard for EPDs of wood-based construction products (EN 16485:2014; CEN 2014) all deviate from the General Programme Instructions of the International EPD System in that they require or allow for expanding the system investigated to include the avoided environmental burdens of materials replaced through recycling.

The standards divide the life cycle of a construction product into Modules A-C and require that the results be separately reported for each module. A cradle-to-grave EPD includes all three modules. The resulting system can be described as a cut-off approach, where the recycling activities are divided between the product being recycled and the product where the recycled material is used (see Figures 4 and 5). The boundary between the life cycles is defined as the point where the recyclable material becomes a marketable product – the point of end-of-waste.

However, the international standards allow for including a fourth module, Module D, which includes benefits and loads that any net outflow of secondary material and energy causes in subsequent life cycles (ISO 2017, p.19). The recently amended EN 15804 makes Module D mandatory in most EPDs of construction products (CEN 2019, p.15). The European standard specific for wood-based products refers to EN 15804 (CEN 2014, p.10), which makes Module D mandatory also in this standard.

Module D should include the part of the recycling process that belongs to the life cycle where the recycled material is used. It should also include the avoided production of the material substituted through the recycling. A justified value-correction factor (V) should be applied to reflect the difference in functional equivalence when the recycled material does not reach the functional equivalence of the virgin material (CEN 2014, p.21; ISO 2017, p.42; CEN 2019, p.38). This indicates that the environmental burdens of virgin production, recycling and final disposal should be calculated as illustrated in Figure 6.

The recent amendment of EN 15804 includes an informative Annex D, which includes a formula (Equation D.6; CEN 2019, p.68) for calculating the benefits and loads of recycling in Module D:

$E' = (R_2 - R_1) \times (E_{RpostEoW} - E^* \times Q_{Rout}/Q_{Sub})$

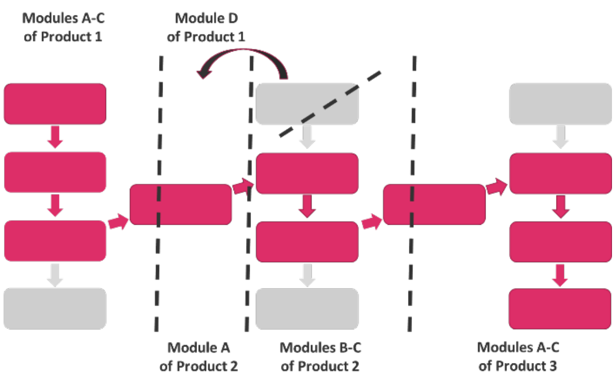

Figure 6: Illustration of the cut-off plus credit method in EN 15804:2012 and EN 16485.

where:

- E' is the environmental burdens of Module D,

- $E_{RpostEoW}$ is the environmental burdens of recycling processes that occur after the outflow of recyclable material reaches the end-of-waste state,
- E* is the environmental burdens of the material replaced through recycling,
- Q_{Rout} is the quality of the recycled material from the life cycle at the point of substitution, and
- Q_{Sub} is the quality of the substituted material.

Equation D.6 in EN 15804 allows for a negative net output of recycled material (if $R_1 > R_2$), which indicates that Module D should be used also in EPDs of products with a net inflow of recycled material, for example Product 3 in our case. However, the equation cannot be applied to Product 3 or other cases where there is no outflow of recycled material ($R_2 = 0$), because $E_{RpostEoW}$, E^*, and Q_{Rout} are all undefined in such cases. Annex D also states that Equation D.6 should be used for calculating loads and benefits related to the export of secondary materials and does not mention imports of secondary material (CEN 2019, p.68). This is in line with the main text of the standard, which states that Module D includes information of consequences arising from materials leaving the product system and replacing other materials in other products (CEN 2019, p.32 & p.37). Based on these observations, we conclude that Module D and Equation D.6 should probably only be used to model consequences of (positive) net outflows of secondary materials and energy.

In our hypothetical case, we get the results presented in Figure 7, if we:

- assume Module D to be included only when there is a net outflow of recycled material (Product 1 in our case),
- assume ¾ of the recycling activities to occur after the end-of-waste, and
- aggregate the results from Modules A-C for increased visibility.

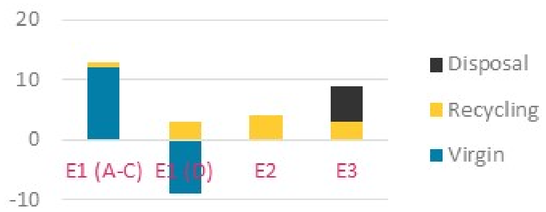

Figure 7: Net total results from our interpretation of the cut-off plus credit method in EN 15804:2012 and EN 16485 applied in our hypothetical case.

Modules A-C fit well in the context of ALCA, because they include no process beyond the boundaries of the product life cycle. Module D, however, includes consequences arising outside the product life cycle as a consequence of producing and using the product: the avoided burdens of material production substituted by the outflow of recycled material. As stated in the Introduction, such information can muddle the results of an ALCA, which aims to identify the share of the global activities and their environmental burdens that belong to the product system. However, the information on consequences occurring beyond the life cycle of the product fits in the context of CLCA, which aims at estimating how the global environmental burdens are affected by the production and use of the product.

When the results of Module D are included in the calculation, with Module D applied only for net outflows of recycled material:

$E_1 + E_2 + E_3 = 13 – 6 + 4 + 9 =20$,

which is less than the total environmental burdens of virgin material production, recycling and waste disposal in the recycling cascade ($E_{Tot} = 26$). Hence, the calculation does not generate additive results. This is because Module D gives Product 1 credit for the virgin material production avoided through recycling (12-¾×4 = 9), but no other product carries the burden to balance this credit. Furthermore, if total results for Modules A-D are reported, the environmental burdens of recycling processes that occur after the outflow of recyclable material reaches the end-of-waste state ($ER_{postEoW}$) are counted twice: both in Module D of Product 1 and in Module A of Product 2 (see Figure 6).

This demonstrates the importance of the rule in EN 15804, and related standards, to avoid aggregating Modules A-D; Module D, at least, should be separately reported.

The standards for EPDs of construction products add a specific rule on how to deal with biogenic carbon. Wood-based products are part of the biogenic carbon cycle: CO_2 is captured by growing trees and emitted when the wood is combusted or decays. If the LCA accounts for emissions of biogenic carbon, it typically accounts also for the CO_2 capture in the virgin production of wood. However, the use of recycled wood involves no carbon capture. This means wood users have an incentive to choose virgin wood over recycled wood to be able to claim the climate benefit of CO_2 capture. The incentive can be an obstacle to increased recycling. To remove this obstacle, EN 16485:2014 states that an inflow of wood from another life cycle should be associated with the capture of the biogenic carbon in the wood. To avoid double-counting of the carbon capture, any outflow of wood from the life cycle should be associated with CO_2 emissions corresponding to the biogenic carbon in the wood (CEN 2014, pp.11-15). In the guidance for the implementation of EN 15804, CEN (2016, pp.16-17) makes clear that this rule should be applied for all bio-based materials.

Allocation to material losses

The international standard for LCA, ISO 14044, states that a closed-loop approach applies when a material is recycled into the same product system, or when it is recycled into another product system without changes in the properties of the material (ISO 2006). In our hypothetical case, this would imply that the quality of the material is the same in all three products ($Q_P = Q_2 = Q_3$).

In the technical report ISO TR 14049, ISO (2012, pp.30-33) proposes the following interpretation of the closed-loop approach:

$$E = (1 – R_2) \times E_V + R_2 \times E_R + (1 – R_2) \times E_D$$

The international standard for carbon footprint, ISO 14067, makes the same interpretation but with a more aggregated formula (ISO 2018a, p.51). This interpretation of closed loop means that the environmental burdens of virgin material production and final disposal are attributed to the product life cycle where the material is not recycled and, hence, lost from the technosphere. Therefore, this closed-loop approach is in the present report termed Allocation to material losses. The environmental burdens of the recycling process are allocated upstream, i.e., to the product that supplies recyclable waste material (see Figures 8 and 9).

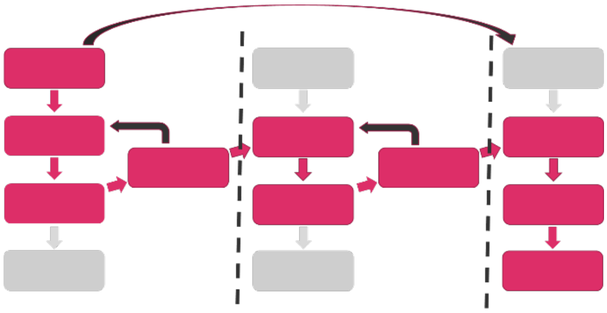

Figure 8: The closed-loop approach proposed by ISO TR 14049, in this report termed Allocation of material losses, allocates the virgin material production to the life cycle where the material is lost and the recycling processes upstream.

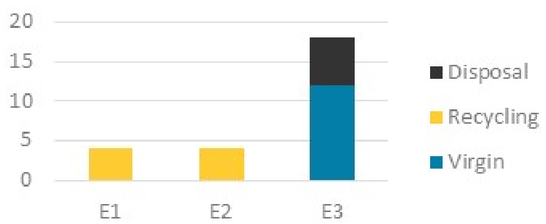

Figure 9: Results from allocation to material losses applied in our hypothetical case.

Allocation to material losses arguably fits in the context of ALCA. As demonstrated by Product 3 in our case, an LCA with this approach might include virgin material production that takes place outside the boundary of the product life cycle. However, as stated in the Introduction, ALCA implies a decision on how the actual virgin production, recycling and final waste management should be allocated between the various products where the material is used. This is consistent with the aim of ALCA to estimate what part of the global environmental burdens belongs to the product.

With this interpretation of ALCA, it goes beyond the product life cycle to what we call the material life cycle. We define this as the system of activities connected by material and energy flows that are part of the product or service investigated, or part of its production, use or waste management. The activities range from the production of virgin material, through (possibly multiple cycles of) manufacturing processes, use, and recycling, until the final waste management of material that is no longer recycled.

Consequential approaches to modeling recycling focus on the foreseeable consequences and, hence, accounts for processes avoided through recycling. A consequential version of allocation to material losses can easily be constructed and is sometimes used:

$E = E_V + R_2 \times (E_R - E^*_V) + (1 - R_2) \times E_D$

where E^*_V is the environmental burdens of the virgin production avoided through recycling. The attributional and consequential equations will give different results if $E^*_V \neq E_V$. The difference might be large if a recycled material (e.g., plastics) replaces a completely different type of material (e.g., wood) in the new product.

The attributional and consequential versions of this method both reflect the view that material lost from the technosphere must be replaced through virgin material production. The environmental benefits of recycling are attributed to products that are recycled after use. This means the method gives incentives to develop recyclable products and to recycle them after use, as long as the combined environmental burdens of virgin material production and final disposal are greater than the burdens of recycling ($E_V + E_D > E_R$). This difference is typically quite large, which means that the incentive to recycle the product after use is strong. As demonstrated by Figure 9, the LCA results in our case strongly depend on to what extent the product is recycled after use (R_2).

However, the method gives no incentive to use recycled material. The share of recycled material in the product (R_1) does not affect the results at all.

This method is relatively easy to apply. The LCA might require data on virgin material production even when the product contains no virgin material (cf. Product 3 in our case). However, global or regional average data on virgin material production are in most cases easy to find in databases.

PAS 2050 and the GHG Protocol both call the attributional interpretation of allocation to material losses the closed-loop approximation. Like ISO (2006, 2012), PAS 2050 recommends the method for cases where the recycled material maintains the same inherent properties as the virgin material input (BSI 2011, p.31). The GHG Protocol recommends the method in cases when (WRI & WBCSD 2011, p.74):

- the recycled content in the product is unknown, because recycled and virgin material cannot be distinguished on the market,
- the demand for recycled material exceeds the supply of recyclable material, or
- the product service life is short and/or well known.

In many of these cases, the GHG Protocol recommends the use of two methods in parallel to assess the robustness of the results: the closed-loop approximation (allocation to material losses) and the recycled-content approach (simple cut-off; see above).

Allocation to material losses is also known as the 0/100 method or the end-of-life approach (WRI & WBCSD 2011, p.71). The Handbook of the International Reference Life Cycle Data System (ILCD) calls it the recyclability substitution approach (EC 2010, pp.354-364).

Worldsteel (2017, pp.16-17) recommends a similar method for modeling of steel recycling. They refer to the closed-loop approach of ISO 14044, which indicates that they consider the inherent properties of the steel to be unaffected by the use and recycling of the steel. However, they explicitly account for material losses in the recycling process. Their equation includes a Factor Y, which is the yield in the electric arc furnace where steel scrap is remelted. The Worldsteel method is developed for LCA of steel but can easily be transferred to other materials. If R_2 is interpreted not as the material collected for recycling but as the material that is actually recycled into other products, the method is identical to the method presented in this section. In any case, there are no material losses in the recycling processes in our hypothetical case, which means that the results in Figure 9 are valid also for the Worldsteel method.

The recent international standard for life cycle inventory (LCI) of steel products (ISO 20915) explicitly states that steel is recycled without loss of inherent properties and prescribes the same method as Worldsteel (ISO 2018b, pp.16-17).

Recycling of stainless steel involves also the recycling of the alloy metals in the steel. The International Stainless Steel Forum (ISSF) recommends the same method as Worldsteel with the addition that the alloy metals in the recycled steel are assumed to substitute the same quantity of virgin alloy metals in the new product (Fuji et al. 2005). This reflects the assumption that the alloy metals are actually needed in the new product. Kaplin (2019) argues that this assumption is reasonable, because the recycling of stainless steel involves the mixing of different scrap fractions to produce well-defined types of stainless steel. Still, the ISSF method reflects the best-case outcome of recycling stainless steel products after use, because it assumes 100% of the recycled steel to replace virgin material and 100% of the alloy metals to replace virgin alloy metals. Like other version of the allocation to material losses, the ISSF method gives no incentive to the use of scrap material.

Allocation to virgin material use

The opposite interpretation of a closed-loop approach is to define the flow in the loop by the input of recycled material into the product (R_1; Figure 10). With this approach the environmental burdens of virgin production and final disposal are both allocated to the products where the virgin material is used:

$$E = (1 - R_1) \times E_V + R_1 \times E_R + (1 - R_1) \times E_D$$

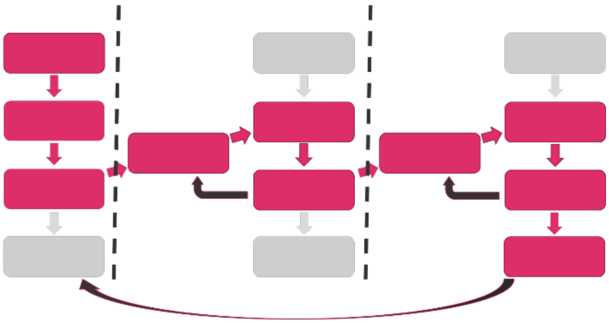

Figure 10: Allocation to virgin material use means that the final waste disposal is allocated to the product using virgin material, while recycling processes are allocated downstream.

Just like allocation to material losses, this method arguably fits in the context of ALCA. The formula does not involve any avoided processes. An LCA with allocation to virgin material use might include waste management outside the boundary of the product life cycle (e.g., Product 1 in our case). However, this is the final waste management of the material used in the product and part of the material life cycle. An LCA with allocation to virgin material use includes no avoided processes or other processes beyond the boundaries of the material life cycle.

A consequential version of this method would focus on the foreseeable consequences and, hence, accounts for processes avoided through the use of recycled material:

$$E = (1 - R_1) \times E_V + R_1 \times (E_R - E^*_D) + E_D$$

where E^*_D is the environmental burdens of the disposal avoided through recycling. The attributional and consequential equations will give different results if $E^*_D \neq E_D$. The difference in results might be large if, for example, one of the disposal processes is landfilling and the other is incineration.

Both versions of the method typically give a strong incentive to the use of recycled material, but no incentive to recycle the product after use. As demonstrated by Figure 11, the LCA results in our case strongly depend on to what extent recycled material is used in the product. However, the rate of recycling after use (R_2) is not part of the equation and, hence, has no effect on the LCA results.

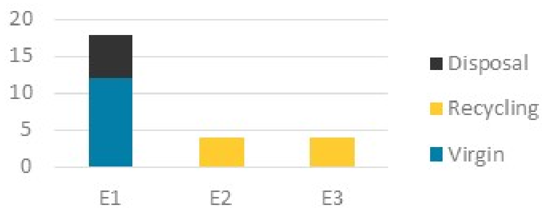

Figure 11: Results from allocation to virgin material use applied in our hypothetical case.

Allocation to virgin material use reflects the view that material extracted from nature will eventually end up as waste. It was discussed by Östermark & Rydberg (1995) but is not recommended by any guideline or standard that we have found.

This method requires information on the final disposal of the material recycled after use in the product investigated. If the material is combustible the environmental burdens of the final disposal depend heavily on whether the disposal is combustion or landfilling. This, in turn, varies between products and locations. When making an LCA of a product containing virgin material (Product 1 in our case), we often do not know what kind of product the material will be recycled into and where this product will be used. The actual waste management for the last product where the material is used (Product 3 in our case) is even less certain. If the actual waste disposal is unknown, assumptions must be made. This significantly reduces the precision of the results of LCAs that contain virgin plastics, paper and wood. For steel, glass and other non-combustible materials, the final disposal is less important for the environment: no energy is recovered at incineration and the materials are relatively inert at landfills. For these materials, the lack of knowledge regarding the actual waste disposal is less important for the LCA results.

50/50 methods

For an LCA aiming to identify environmental key issues in the product life cycle, the Nordic Guidelines on LCA (Lindfors et al. 1995, pp.63-64) recommend a 50/50 method. With this method the environmental burdens of virgin material production and final disposal are split equally between the product using the virgin material and the product where the material is lost from the technosphere. The environmental burdens of each recycling process are split equally between the product system supplying recyclable material and the product where the recycled material is used (Figure 12).

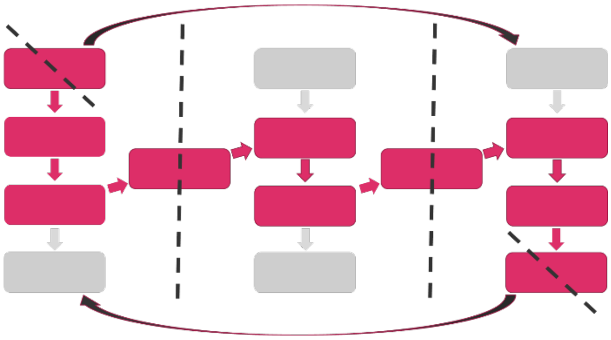

Figure 12: The 50/50 method recommended by Lindfors et al. (1995) for identifying key issues in product life cycles.

The environmental burdens of virgin material production, recycling and waste disposal for any product is calculated according to the following equation (see also Figure 13):

$$E = 0.5 \times [(1 - R_1) + (1 - R_2)] \times (E_V + E_D) + 0.5 \times (R_1 \times E_{Rin} + R_2 \times E_{Rout})$$

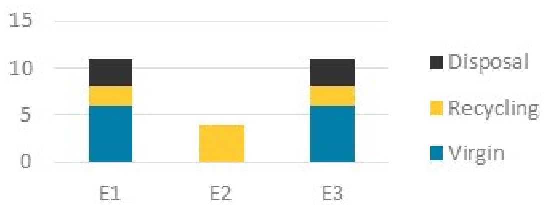

Figure 13: Results from all 50/50 methods applied in our hypothetical case.

This 50/50 method can also be interpreted as a closed-loop approach where the flow in the closed loop is defined as the average of the input and output of recycled material across the boundary of the life cycle (R_1 and R_2, respectively; Figure 14). In this sense, the method is a compromise between allocation to material losses and allocation to virgin material use.

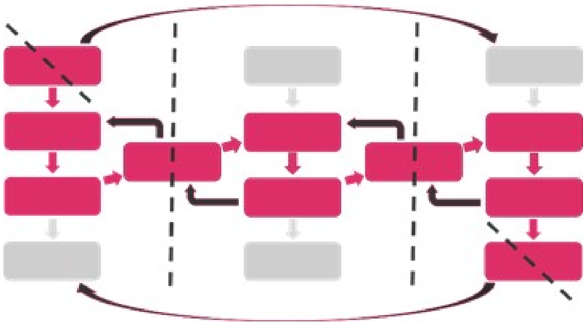

Figure 14: The 50/50 method described as a closed-loop approach.

This 50/50 method arguably fits in the context of ALCA, because it does not account for any avoided processes and no processes beyond the boundaries of the material life cycle.

Consequential versions of the 50/50 method have also been proposed. For example, Ekvall (2000) presented a 50/50 method focusing on processes outside the life cycle studied: the virgin material production, recycling, and final disposal of other products affected by the flows of recycled material across the boundary of the life cycle studied. The attributional and consequential 50/50 approaches yield different results if, for example, $E^*_V \neq E_V$ or $E^*_D \neq E_D$. In our hypothetical case, however, a consequential version of the 50/50 method would yield the same results as in Figure 13, since we assume the same burdens for all virgin production processes, for all recycling processes, and for all disposal processes.

All 50/50 methods reflect the view that 1) material use requires both virgin material production and final disposal, and 2) supply of and demand for recyclable material are both necessary for recycling to take place. The environmental benefits of recycling are equally attributed to products that are recycled after use and products that contain recycled material. This means the method typically gives incentives to the use of recycled material as well as to recycling of products after use, when recycling brings an environmental benefit ($E_V + E_D > E_R$).

However, the incentive to recycle a product can disappear if final disposal brings a net environmental benefit ($E_D < 0$). This could happen for paper materials, if the final disposal is energy recovery through incineration. The LCA results will in such cases give an incentive to recycle the product only if half the environmental benefit of recycling is more than the benefit of final disposal. This means the net environmental benefit of disposal must be less than a third of the difference between the burdens of virgin production and recycling:

$$0.5 \times (E_V + E_D - E_R) > -E_D \quad => \quad E_V - E_R > -3E_D$$

The 50/50 methods are slightly more complex than the methods described in previous subchapters. Compared to allocation to virgin material use, the 50/50 methods can require the additional collection of data on virgin material production. Since such data are typically easily available, 50/50 methods are not much more difficult to apply than allocation to virgin material use.

Quality-adjusted 50/50 methods

Allacker et al. (2017) review 11 different methods for modeling recycling as part of the EU process to develop methods for Environmental Footprints. They use three criteria in their assessment of the methods (see also Annex 2):

- physical realism, which is the extent to which the model correctly represents the flows and related mass balances on a product and systems level,
- the fairness of the distribution of burdens and benefits between products, and
- practicality, which is the feasibility of the method and the range of its applicability.

Based on their assessment they propose a modified version of an approach that was previously suggested by Association Française de Normalisation (AFNOR 2011): BPX 50/50. The method proposed by Allacker et al. (2017) resembles the 50/50 method of Ekvall (2000) but accounts for the quality of material recycled from the investigated product (Q_S). The environmental benefit credited to a life cycle that generates recycled material is proportional to the quality of this recycled material (see also Figure 15):

$$E = (1 - R_1) \times E_V + 0.5R_1 \times (E_{Rin} + E_V - E^*_D) + 0.5R_2 \times (E_{Rout} - Q_S/Q_P \times E^*_V + E_D) + + (1 - R_2) \times E_D$$

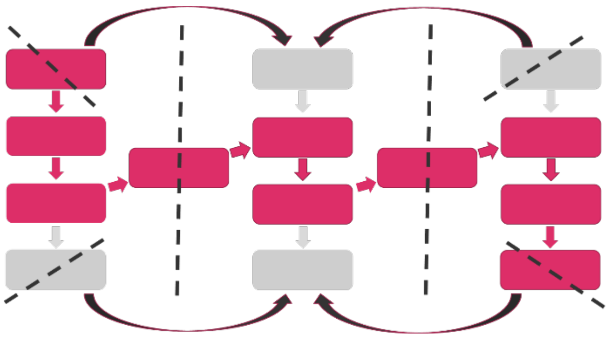

Figure 15: Illustration of how the quality-adjusted 50/50 method suggested by Allacker et al. (2017) applies to Product 2.

Figure 16 shows the results of the method in our hypothetical case, accounting for the fact that the quality of material degrades in the recycling processes: $Q_P > Q_2 > Q_3$.

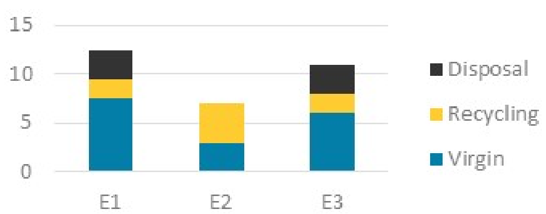

Figure 16: Results from the quality-adjusted 50/50 method proposed by Allacker et al. (2017), applied in our hypothetical case.

Note that the approach of Allacker et al. (2017) is asymmetric in the sense that the environmental credit assigned to recycled material leaving a product system is different from the environmental burden assigned to the recycled material when it enters the next product system. The credit awarded to products supplying recycled material is reduced to reflect the lower quality of recycled material; however, the burdens assigned to products using the recycled material is not correspondingly reduced. This means that the results from this method are not additive. The sum of environmental burdens associated with each product is greater than the total environmental burdens of the cascade. In our hypothetical case:

$E_1 + E_2 + E_3 = 12.5 + 7 + 11 = 28.5$,

which is greater than 26, the total environmental burdens of virgin material production, recycling and waste disposal in the recycling cascade.

The asymmetry of the approach of Allacker et al. (2017) was one of the reasons why it was replaced by the Circular Footprint Formula (CFF; see below) in the PEF methodology. AFNOR (2016, pp. 29-33) has also presented revised guidelines with a new formula for modeling recycling.

The German Umweltbundesamt (UBA) issued guidelines on LCA of beverage packaging that require a 50/50 method to be used as the reference case. Sensitivity analyses must be made with both 100/0 and 0/100 allocation methods (Detzel et al. 2016, p.430). In cases when recycled material (e.g., plastics), replaces another kind of material (e.g., steel or wood), the LCA should include data on the material that is actually replaced.

The 50/50 method of Detzel et al. (2016, p.430) also accounts for degradation of material quality. When the recycled material has lower quality than the corresponding virgin material, the calculation should include a substitution factor ($S < 1$), implying that 1 kg of recycled material replaces less than 1 kg of virgin material. Detzel et al. (2016) do not state how to define and calculate this substitution factor, nor present the formula that should be used to model recycling. An interpretation of the text must be made to make the UBA method operational. In our interpretation, environmental burdens of virgin material production, recycling and waste disposal for a product are calculated according to an equation similar to the one recommended by Allacker et al. (2017; see also Figure 15):

$$E = (1 - R_1) \times E_V + 0.5R_1 \times (E_{Rin} + E_V - E^*_D) + 0.5R_2 \times (E_{Rout} - S \times E^*_V + E_D) + $$
$$+ (1 - R_2) \times E_D$$

If the substitution factor S is defined as the quality of the recycled material divided by the quality of virgin material, the two quality-adjusted 50/50 methods are identical.

Both quality-adjusted 50/50 methods fit poorly in an ALCA context, because they expand the boundaries of the system investigated to include avoided virgin production and waste disposal. They would have fit well in the context of CLCA if they had accounted for material quality or substitutability in the inflow as well as the outflow of recyclable material. Such approaches reflect the view that the more a material degrades, the sooner it will have to be disposed of and replaced by virgin material.

The Circular Footprint Formula

The current PEF methodology includes an approach to model material recycling as well as energy recovery at the end of the product life cycle (EC 2018, pp.110-130; Zampori & Pant 2019, pp.65-75). This approach is called the Circular Footprint Formula (CFF) and takes into account the share of recycled material (R_1), the ratio of material recycling at the end of the life cycle (R_2), the quality of recycled material entering and leaving the life cycle (Q_{Sin} and Q_{Sout}, respectively), and the balance between supply and demand for individual recycled materials. As a result, the CFF is fairly complex. The environmental burdens of virgin material production, recycling and waste disposal for a product is calculated according to the following equation:

$$
\begin{aligned}
&E = (1 - R_1) \times E_V + R_1 \times [A \times E_{Rin} + (1 - A) \times E_V \times Q_{Sin}/Q_P] + \\
&+ (1 - A) \times R_2 \times [(E_{Rout} - E^*_V \times (Q_{Sout}/Q_P)] + (1 - R_2) \times E_D = \\
&= [1 - R_1 + R_1 \times (1-A) \times Q_{Sin}/Q_P] \times E_V - (1 - A) \times R_2 \times (Q_{Sout}/Q_P) \times E^*_V + \\
&+ AR_1 \times E_{Rin} + (1 - A) \times R_2 \times E_{Rout} + (1-R_2) \times E_D
\end{aligned}
$$

This version of the equation is a simplification of the original CFF because, in parallel to the other equations in this report, we have combined the net environmental burdens of energy recovery, landfilling and other disposal processes into a single variable: E_D.

The CFF accounts for the balance between supply and demand for recycled material through the material-dependent Factor A, which aims to reflect market realities. This factor gives different weight to R_1 and R_2 in the equation, i.e. to the use of recycled material in the life cycle and to the quantity of recycled material supplied by the life cycle. Factor A can vary between 0.2 and 0.8, depending on the balance between total supply and demand for the recycled material on the market. EC (2018b) recommends the low value A = 0.2 for metals, glass and most paper materials. Such a low A value indicates that the demand for recycled material exceeds the supply (EC 2018, p.114). It gives a larger weight to R_2 compared to R_1. As illustrated by Figure 17, most of the recycling processes are allocated upstream. Product 2 in our hypothetical case carries part of the burdens of virgin material production (E_V), but also gets credit for part of the avoided virgin material production in Product 3 (E^*_{V3}). The material quality degrades in the recycling processes ($Q_P > Q_2 > Q_3$), and Products 1 and 2 carry part of the environmental burdens of virgin production because of this degradation in quality (see Figure 18).

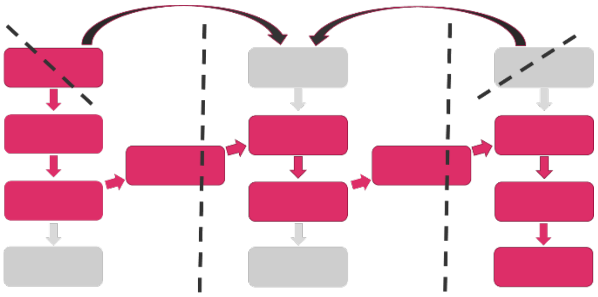

Figure 17: Illustration of how the CFF applies to Product 2 when the material-specific Factor A is 0.2, which is recommended for metals, glass and most paper fractions.

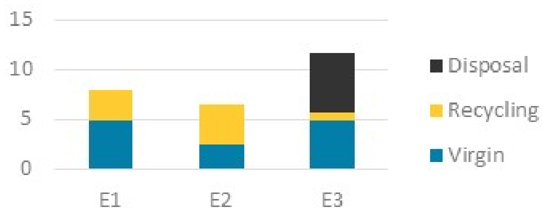

Figure 18: Results from the CFF of the PEF methodology applied in our hypothetical case, when Factor A = 0.2.

For tissue paper and plastics, EC (2020) recommends A = 0.5, which indicates that supply and demand are in equilibrium (EC 2018, p.114). This gives equal weight to R_2 and R_1, which means that the recycling processes are allocated 50/50 (see Figure 19). Compared to the (simple) 50/50 methods above, Products 1 and 2 carry a larger part of the virgin production, because the CFF takes into account the loss of material quality in these life cycles (cf. Figures 11 and 20).

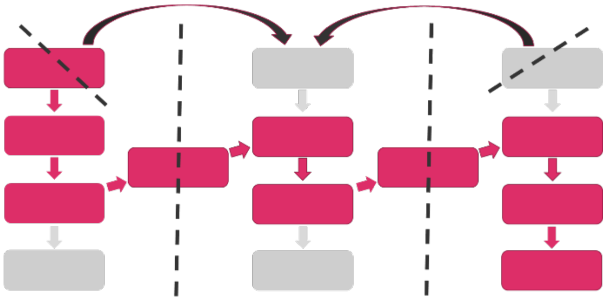

Figure 19: Illustration of how the CFF applies to Product 2 when the material-specific Factor A is 0.5, which is recommended for plastics and tissue paper.

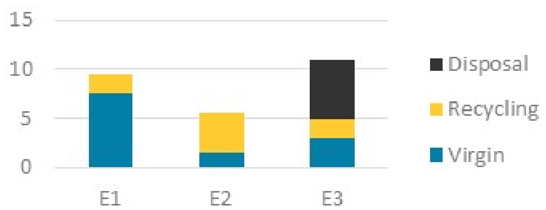

Figure 20: Results from the CFF applied in our hypothetical case, when Factor A = 0.5.

Results calculated with the CFF typically indicate environment benefits from the use of recycled material and from recycling of products after use. They also indicate that the quality of the materials used and recycled should be safeguarded, and that high-quality material should not be used where degraded material is sufficient. The strength of all these incentives varies between materials and depends on Factor A as well as on the quality losses in the use and recycling of the material.

With the low Factor A = 0.2 recommended for many materials, the CFF gives a rather weak incentive to use recycled material with a quality similar to virgin material. In other words, it gives a weak incentive to use most recycled metals. The incentive to use recycled paper and polymers is greater because these materials degrade in the recycling loops. For polymers, EC (2020) also recommends a higher value on A: 0.5 (EC 2020). This further increases the incentive to use recycled instead of virgin polymers where this is possible.

The CFF gives an incentive to safeguard the quality of the material in the life cycle and, in most cases, to recycle high-quality material after use. However, the incentive to recycle material after use can disappear in the CFF calculations if the disposal processes bring a net environmental benefit ($E_D < 0$), if:

$$(1 - A) \times (E_{Rout} - E^*_V \times Q_{Sout}/Q_P) > E_D$$

This can happen even when a high recycling rate is environmentally beneficial at the societal level, particularly if the Factor A is high and the quality of the material to be recycled is low. For example, there is a risk that CFF results indicate that collection for recycling of wastepaper is bad for the environment, even in cases when recycling is good for the environment (i.e., when $E^*_V + E_D - E_R > 0$).

The CFF arguably fits in a CLCA, because it accounts for the virgin material production avoided through recycling. Factor A can then be interpreted as an estimate of to what extent the use of a recycled material, or the recycling after use of the material, will contribute to increasing the total recycling of this specific material. A drawback, in the context of CLCA, is that the CFF does not account for the waste disposal avoided through the use of recycled material.

The CFF is more complex to apply than the methods above, because it involves many parameters: it requires data on material quality, Factor A, etc. However, EU provides detailed guidance (EC 2018, pp.111-124) and default data on the parameters for several important materials (EC 2020). This makes the approach feasible to apply in LCAs of many products.

Market price-based allocation

The international standard for carbon footprint (ISO 14067) builds upon the standard for LCA (ISO 14044) just like, for example, PAS 2050 and the GHG protocol. Similar to ISO 14044 and PAS 2050, ISO 14067 recommends an open-loop approach for cases when a material is recycled into another product while undergoing a change to its inherent properties. However, when PAS 2050 and the GHG protocol select the simple cut-off or recycled-content approach for modeling the open-loop, ISO 14067 argues that the virgin material production needs to be partitioned between the product where the virgin material is used and the product where the material is lost.

Just like the CFF, the open-loop approach of ISO 14067 includes a material-specific allocation Factor A. However, ISO 14067 defines this factor differently: as the ratio between the global market value of scrap material or recycled material to the global market value of virgin material (ISO 2018a, p.53). This definition is based on ISO 14044, paragraph 4.3.4.3.4, which states that the allocation can be based on the market value of scrap material or recycled material in relation to the market value of virgin material.

With this definition, Factor A has the opposite role in ISO 14067, compared to in the CFF: if A is close to zero, ISO 14067 gives a greater weight to the use of recycled material (R_1), but if A is close to 1 the supply of recycled material (R_2) is the important variable. The environmental burdens of virgin material production, recycling and waste disposal for a product is calculated according to the following equation (ISO 2018a, p.53):

$$E = R_1 \times A \times E_V + R_1 \times E_{PP} + (1 - R_1) \times E_V + E_{EoL} - R_2 \times A \times E_V =$$
$$= [1 - R_1 + A \times (R_1 - R_2)] \times E_V + R_1 \times E_{PP} + E_{EoL}$$

Where:

- E_{PP} is the GHG emissions of “pre-processing of the recycled material in order to fulfil the quality requirements of the substituted virgin material”, and
- E_{EoL} is “the GHG emissions tied to end-of-life operations” in the life cycle that generates the recyclable material.

Cederstrand et al. (2014) and Hohenthal et al. (2019) interpret E_{PP} to be the environmental burdens of the recycling process (E_R) and E_{EoL} to be the environmental burdens of the treatment of waste that is not recycled [$(1 - R_2) \times E_D$]. This implies that we can express the calculation in similar terms as the other methods:

$$E = [1 - R_1 + A \times (R_1 - R_2)] \times E_V + R_1 \times E_{Rin} + (1 - R_2) \times E_D$$

With this approach, the final disposal is allocated to the product that is not recycled after use. Each recycling process is allocated to the product produced from the recycled material. The allocation of virgin material production depends on the price-based Factor A. The approach arguably fits in an ALCA, because the formula does not involve any avoided processes and no processes beyond the boundaries of the material life cycle.

The fact that ISO 14067 does not specify where the Factor A should reflect the market value of recycled or scrap material makes the method somewhat vague. If it reflects the market value of a recycled material that is a fair but not a perfect substitute for virgin material, A = 0.8 is a possible value. This would mean that most of the virgin material production is allocated to the product that is not recycled after use (see Figures 21 and 22).

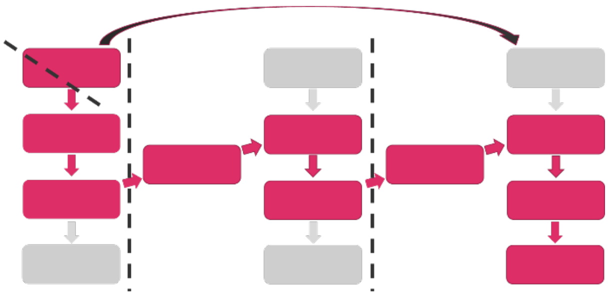

Figure 21: Illustration of price-based allocation when the price ratio of recycled to virgin material (A) is 0.8.

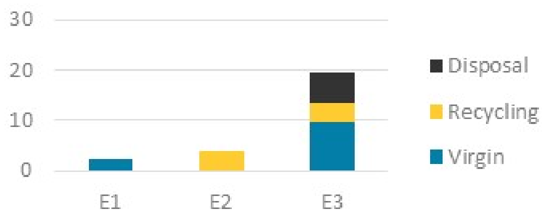

Figure 22: Results from price-based allocation in our hypothetical case, when A = 0.8.

If Factor A is instead based on the market value of scrap material, A = 0.2 is a more likely value. With this value, most of the virgin material production is allocated to the product that is produced from virgin material, and the approach resembles the cut-off approach used for open-loop modeling in PAS 2050 and the GHG protocol (see Figures 23 and 24).

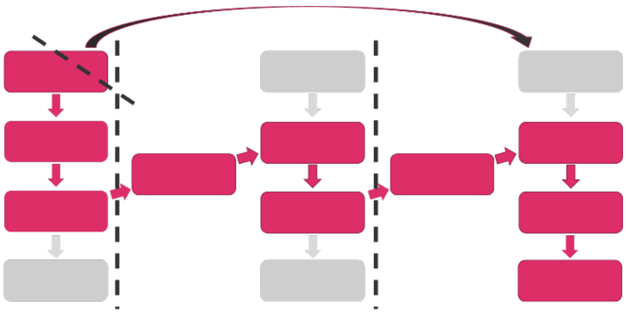

Figure 23: Illustration of price-based allocation when the price ratio of recycled to virgin material (A) is 0.2.

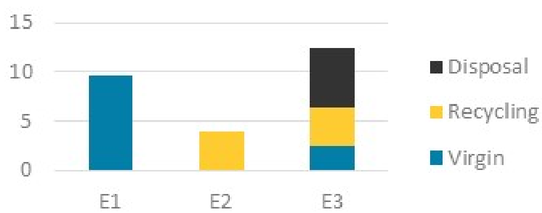

Figure 24: Results from price-based allocation in our hypothetical case, when A = 0.2.

The price-based allocation recommended in ISO 14067 is less complex, compared to the CFF. An accurate application requires, however, that the boundary between forwarding recyclable material and the actual recycling process is defined. It also requires data on the market value of virgin and recycled (or recyclable) material.

As evident from Figure 22, the approach can give a huge incentive not to waste the material but to recycle it after use, if the market value of recycled (recyclable) material is high. Product 3, which is not recycled, gets most of the environmental impacts from virgin material production, recycling and final disposal in our calculation. However, the approach gives very little incentive to the use of recycled material. On the contrary, Product 2 (produced from 100% recycled material) gets a higher environmental burden than Product 1 (produced from 100% virgin material).

Market price-based substitution

Schrijvers et al. (2016a) propose a method with components from both the CFF and the open-loop approach of ISO 14067, but where the environmental burdens of the final disposal (ED) are also included in the allocation problem (see Figure 25). Similar to ISO 14067, this approach includes a price-based Factor A that varies between materials. However, Schrijvers et al. (2016a) defines this factor better and also distinguish between the factor for recycled material used in the product (ARC) and the factor for recycled material from the life cycle (ARRE):

- ARC is the price of consumed recycled material divided by the price of avoided virgin material in the product investigated
- ARRE is the price of recycled material supplied by the life cycle investigated divided by the price of avoided virgin material in the subsequent product.

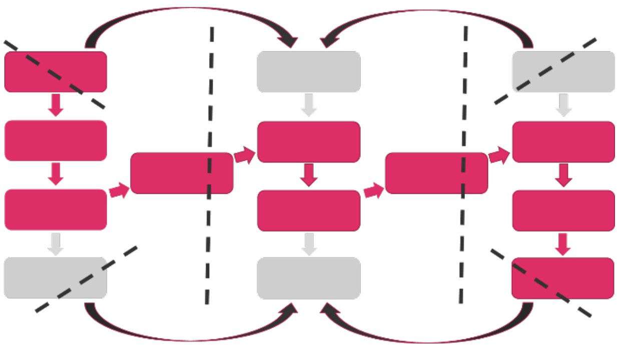

Figure 25: Illustration of how the price-based substitution recommended by Schrijvers et al. (2016a) applies to Product 2 when the price ratio of recycled to virgin material (ARC and ARRE) is 0.8. This could be the case when recycled material is a fair but not a perfect substitute for virgin material.

Using the notation of this report, the environmental burdens of virgin material production, recycling and waste disposal for a product is calculated according to the following equation:

$$E = E_V \times [1 - R_1 \times (1 - Q_{Sin}/Q_P)] + E_D - (1 - A_{RC}) \times R_1 \times (E_V \times Q_{Sin}/Q_P + E^*_D - E_{Rin}) -$$
$$- A_{RRE} \times R_2 \times (E^*_V \times Q_{Sout}/Q^*_P + E_D - E_{Rout}) =$$
$$= (1 - R_1 + R_1 A_{RC} \times Q_{Sin}/Q_P) \times E_V - A_{RRE} \times R_2 \times (Q_{Sout}/Q^*_P) \times E^*_V +$$
$$+ (1 - A_{RC}) \times R_1 \times E_{Rin} + A_{RRE} \times R_2 \times E_{Rout} + (1 - A_{RRE} \times R_2) \times E_D - (1 - A_{RC}) \times R_1 \times E^*_D$$

Where the asterisk indicates the environmental impact of avoided processes (E^*D, etc.) and the quality of replaced material (Q^*P).

If ARC and ARRE are both 0.8, the price-based substitution gives approximately the same results as the CFF when A = 0.2 (Figure 18). The difference is that part of the final disposal is now allocated to the product produced from virgin material (see Figure 26).

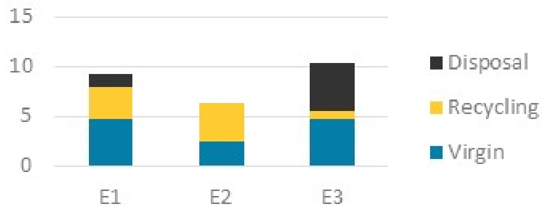

Figure 26: Results from price-based substitution in our hypothetical case, when ARC=ARRE=0.8.

Price-based substitution fits well in a CLCA, because it accounts for the virgin material production avoided through recycling, and for the waste disposal avoided through the use of recycled material. It reflects the view that the more a recycled material loses in economic value, the sooner it will be disposed of and replaced by virgin material.

The approach of Schrijvers et al. (2016a) gives a clear incentive to recycle metals and other materials that have a similar quality and value after recycling as the virgin material. However, similar to the CFF this approach can eliminate the incentive to recycle low-grade material after use if the disposal processes bring a net environmental benefit ($E_D < 0$), even when a high recycling rate is environmentally beneficial at the societal level.

This method is even more complex to apply than the CFF, because it includes more variables and requires more data. It distinguishes between ARC and ARRE and between E_D and E^*_D. It also requires data on the final disposal of materials when the recycling rate (R_2) is 100% and no final disposal takes place in the life cycle investigated.

Price-elasticity methods

Ekvall (2000) presents a conceptual model of the market for a recyclable material. In this model a change in the collection of recyclable material from the life cycle investigated affects the total supply and, hence, the price of recyclable material. This, in turn, affects the use of recyclable material and the collection of recyclable material from other sources in proportion to how sensitive these flows are to a change in the price. Based on this model, Ekvall (2000) proposes to deal with the allocation problem using material-dependent factors that reflect the price elasticity of supply of (η_S) and demand for (η_D) recyclable material. The former is typically positive ($\eta_S > 0$) because an increase in price stimulates an increase in the supply. The latter is negative ($\eta_D < 0$) because an increase in price reduces the demand.

Similar to the quality-adjusted 50/50 method recommended by UBA, this price-elasticity method also includes a substitution factor (S) to account for the fact that 1 kg of recycled material sometimes replaces less than 1 kg of virgin material. However, Ekvall (2000) explicitly states that the approach is symmetric. The market model can be applied to allocate the environmental burdens of virgin material production, recycling, and final disposal (here assuming that the environmental burdens of collecting recyclable materials can be neglected):

$$E = (1 - R_1) \times E_V + R_1 \times E_{Rin} + (1 - R_2) \times E_D +$$
$$+ [R_1/(\eta_S - \eta_D)] \times [\eta_D \times (E_{Rin} - S \times E_V) - \eta_S \times E_D] -$$
$$- [R_2/(\eta_S - \eta_D)] \times [\eta_D \times (E_{Rout} - S \times E_V) - \eta_S \times E_D] =$$
$$= [1 - R_1 + (R_2 - R_1) \times S \times \eta_D/(\eta_S - \eta_D)] \times E_V +$$
$$+ R_1 \times [1 + \eta_D/(\eta_S - \eta_D)] \times E_{Rin} - R_2 \times \eta_D/(\eta_S - \eta_D) \times E_{Rout} +$$
$$+ [1 - R_2 + (R_2 - R_1) \times \eta_S/(\eta_S - \eta_D)] \times E_D$$

Ekvall (2000) presents default data on price elasticities for a few recyclable materials, based on old data from Palmer et al. (1997). For glass bottles the default values are $\eta_S = -\eta_D = 0.5$. Assuming S = 1 for glass, the price elasticity approach results in the same model and results as the 50/50 approach (Figures 12-13).

For PET and HDPE bottles, the default values are $\eta_S = -5\eta_D = 0.5$. With these numbers the use of recycled material (R_1) is five times as important for the results, compared to recycling after use (R_2; see Figure 27). When the substitution factor is 0.8, the approach generates the results in Figure 28.

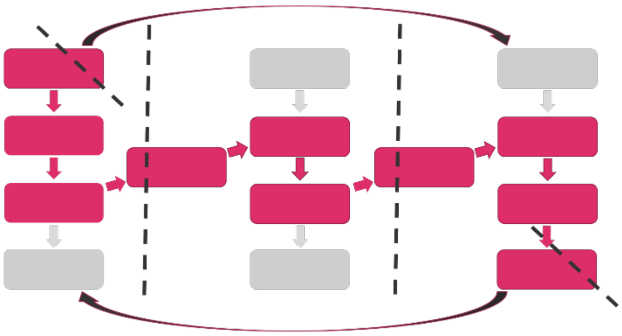

Figure 27: Allocation based on price elasticities $\eta_S = -5\eta_D$, which is consistent with the default values for plastic bottles (Ekvall 2000).

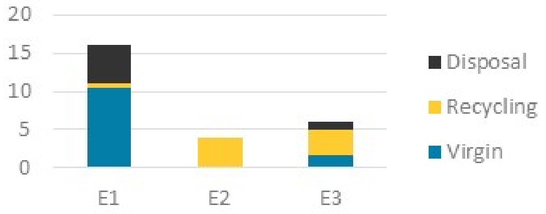

Figure 28: Results from the price-elasticity method in our hypothetical case, when $\eta_S = -5\eta_D$ and S = 0.8, which could be the case for plastic from bottles.

This method arguably fits in an ALCA, because the formula does not involve any avoided processes and no processes beyond the boundaries of the material life cycle. However, the market model can also be applied as a substitution approach fit for CLCA, accounting for the avoided virgin material production and final disposal (see Figure 29):

$$E = (1 - R_1) \times E_V + R_1 \times E_{Rin} + (1 - R_2) \times E_D +$$
$$+ [R_1/(\eta_S - \eta_D)] \times [\eta_D \times (E_{Rin} - S \times E_V) - \eta_S \times E^*_D] -$$
$$- [R_2/(\eta_S - \eta_D)] \times [\eta_D \times (E_{Rout} - S \times E^*_V) - \eta_S \times E_D],$$

where the asterisk indicates that the process is avoided. In our hypothetical case, the results of the substitution approach will be the same as for the allocation approach: Figure 13 shows the results with $\eta_S = -\eta_D$ and S = 1; Figure 28 shows the results with $\eta_S = -5\eta_D$ and S = 0.8.

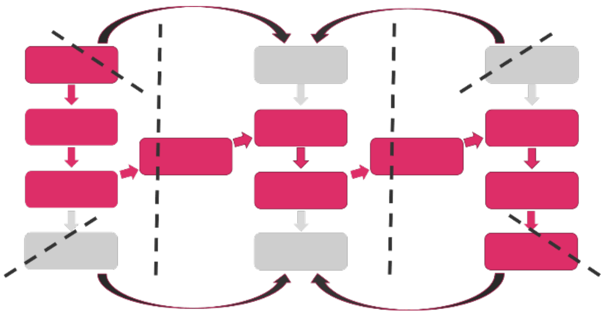

Figure 29: Substitution based on price elasticities $\eta S = -5\eta D$, which is consistent with the default values for plastic bottles (Ekvall 2000). Here the substitution factor S is assumed to be 0.8.

The price-elasticity methods reflect the view that the foreseeable consequences of using or supplying recyclable material depends on how sensitive (i.e., elastic) the demand and supply are on the market for the recyclable material. Similar to several methods above – quality-adjusted 50/50, the CFF, market price-based allocation and substitution – the incentives given by the price elasticity method will vary between materials. When the supply and demand is equally elastic, such as indicated by the default values for glass bottles, this approach will typically give incentives to the use of recycled material as well as to recycling after use. An exception might occur when final disposal brings significant net benefits for the environment.

When the supply of recyclable material is much more elastic than the demand, such as indicated by the default values for plastic bottles, this method gives a clear incentive to the use of recycled material but little incentive to recycling after use, particularly when the final disposal is good for the environment (ED < 0).

Similar to other methods – allocation to material losses or to virgin material use, and the 50/50 method – the price elasticity method does not account for losses in material quality. Hence, it disregards the fact that a downgraded material might be less likely to be recycled again in the future.

Söderholm & Ekvall (2019) observed that markets of recyclable metals and paper are strongly connected to the markets of virgin materials. The price of recycled and virgin material co-varies over time, because virgin and recyclable materials compete in many applications. Hence, markets of recyclable metals and paper should not be separately modelled. It is better to model markets of virgin and recycled material as a single joint market. The most elastic flow on this market is the supply of virgin material. This means a change in the supply of metal or paper scrap for recycling mainly affects the virgin production. A change in the use of metal or paper also mainly affects the virgin production, regardless of whether the material used is virgin or recycled.

For polymers, the mechanisms described by Ekvall (2000) still appear to hold. The overlap in applications of virgin and recycled material is not sufficient to create a single joint market. Instead, the supply and demand of recyclable material can be modelled as a separate market.

Modeling based on price elasticities is less complex than the CFF or the market-price substitution of Schrijvers et al. (2016a) in the sense that it includes fewer parameters. However, estimates of the price elasticity for recyclable materials are scarce. This makes the approach difficult to apply in practice.

The few estimates of the price elasticity presented by Ekvall (2000) are based on very old data. More recent estimates are also likely to be based on old data. The current and future price elasticities remain highly uncertain. This reduces the precision of results generated with price-elasticity approaches.

Allocation at the point of substitution

Allocation at the point of substitution (APOS) is a method used in the Ecoinvent database. It is designed to deal with waste flows that can be converted into useful products, for example through incineration with energy recovery. When the waste is recycled, the APOS method means that the same allocation factors are applied to the activity that generates the waste, to the recycling process, and to the disposal of the share of the waste that is not recycled (Wernet et al. 2016). A part of the impact of these processes is allocated to the product of the waste-generating activity. The rest is allocated to the recycled material. The allocation is typically based on revenues for the product and recycled material; an exception is made when the price does not reflect the "true value" of the products (Weidema et al. 2013). Since consumer products are generally much more expensive than the material in these products, the economic allocation means the share allocated to the recycled material tends to be quite small.

When the material recycled is post-consumer waste, we assume that the activity generating the waste is the full life cycle of the recycled product, and that the allocation partitions the environmental burdens between this product and the recycled material. In other words, the allocated burdens include burdens from virgin material production, but also from the manufacturing processes and the use phase of the product that is recycled after use. This interpretation is consistent with Jolliet et al. (2015) who argues that plastics recycled from agricultural processes would carry part of the nitrate emissions from the agriculture. It is also consistent with Pré (2019) that states that APOS can assign larger environmental burdens to recycled metals, compared to the corresponding virgin metals.

Figure 30 illustrates how the APOS approach plays out in our hypothetical case where either 100% or 0% of the post-consumer waste is recycled. Here we assume that 90% of the burdens of each life cycle is allocated to the product and 10% to the recycled material generated at the end of the life cycle. Ten percent of the virgin material production, manufacturing and use of Product 1 are allocated to the material that is recycled into Product 2 and, hence, included in the burdens of the second life cycle. Ten percent of these burdens are allocated to Product 3. This means that 1% of the burdens of the first life cycle is allocated to Product 3.

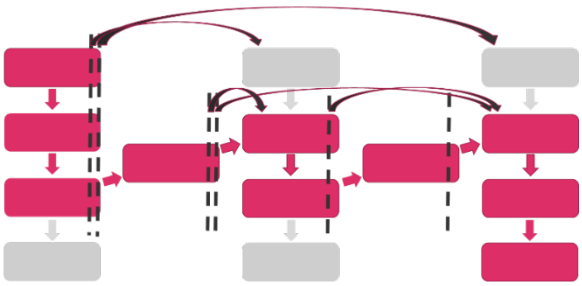

Figure 30: Allocation at the point of substitution (APOS) when 90% of the life-cycle burdens are allocated to the product and 10% to the recycled material.

Figure 31 presents the results in our hypothetical case, when the environmental burdens of manufacturing and use is assumed to be 20 for each of the products, and when 90% of the burdens of each life cycle is allocated to the product and 10% to the recycled material. Note that the results include the environmental burdens of the full life cycles, in contrast to the results in Figures 3, 5, 7, 9 etc. that only include the burdens of virgin material production, recycling and final waste disposal.

As illustrated by Figures 30-31, APOS allocates all of the final disposal to the product life cycle where final disposal occurs. It is likely to allocate most of the virgin material production to the product that is produced from virgin material. However, contrary to the cut-off approaches, most of the recycling process is likely to be allocated to the life cycle that generates recyclable material.

Figure 31: Results from the APOS approach in our hypothetical case, including the environmental burdens of the full life cycles.

This method arguably fits in an ALCA, because the formula does not involve any avoided processes and no processes beyond the boundaries of the material life cycle. However, part of the manufacturing and use of a product is allocated to the recycled material from that product, which means the recycled material can carry environmental burdens that are seemingly unrelated to materials production. Jolliet et al. (2015) mentions the example of plastics recycled from agricultural processes that would carry part of the nitrate emissions from the agriculture.

If the manufacturing and use of a product have much larger environmental impacts compared to the materials production, the recycled material from this product can carry more environmental burdens than virgin material. This means that the method can give producers an incentive to choose virgin material over recycled material, even when a high rate of recycling is environmentally beneficial for the society.

Reflections

The methods above differ not only in the approach to deal with the allocation problem at materials recycling, but also in how the allocation problem is defined (Table 2). With the *simple* and *economic cut-off methods*, the allocation problem just concerns how to allocate the recycling activities. Most other methods include the virgin material production in the allocation problem. Some of them, in addition, include the final disposal of the material. *Allocation at the point of substitution (APOS)* considers recyclable material to be a by-product of the life cycle where it is generated. This means the problem is how to allocate impacts from the whole life cycle.

Table 2: What is the allocation problem? Life cycle phases requiring allocation in different approaches to modeling recycling.

Method	Virgin production	Manufacturing	Use	Recycling	Disposal
Simple cut-off				X	
Economic cut-off				X	
Cut-off plus credit	X			X	
Allocation to material losses	X			X	
Allocation to virgin material use	X			X	X
50/50 methods	X			X	X
Quality-adjusted 50/50	X			X	X
Circular Footprint Formula	X			X	
Price-based allocation	X			X	
Price-based substitution	X			X	X
Price-elasticity methods	X			X	X
APOS	X	X	X	X	

As discussed above, different methods fit in the context of ACA and CLCA (Table 3). The *simple* and *economic cut-off methods* fit well in ALCAs, because they include nothing but the product life cycle. The use of several other methods in ALCA can also be defended: although they include processes and other activities beyond the product life cycle, they only include activities in the material life cycle.

Table 3: Does the method fit in attributional or consequential LCA?

Method	Attributional LCA	Consequential LCA
Simple cut-off	X	
Economic cut-off	X	
Cut-off plus credit	X (Modules A-C)	X (Module D)
Material losses	(X)	X
Virgin material use	(X)	X
50/50 methods	(X)	X
Quality-adjusted 50/50		X
Circular Footprint Formula		X
Price-based allocation	(X)	
Price-based substitution		X
Price-elasticity methods	(X)	X
APOS	(X)	

Approaches that include avoided activities fit better in CLCA. Not all of them accurately reflect foreseeable consequences of using or supplying recyclable materials, however. Further analysis is required to decide which method most accurately reflect these consequences.

Several methods can be made to fit in both ALCA and CLCA, depending on whether the virgin material production and final disposal are the actual processes in the material life cycle, or the activities avoided through recycling. When *cut-off plus credit* is applied, Modules A-C generate results that fit well in an ALCA, while Module D generates results that can fit in a CLCA.

As also discussed above, the methods reflect different views on recycling and on materials in the society, e.g.:

- *Allocation to material loss*: when a material is lost from society, it must be replaced by virgin material.
- *Allocation to virgin material use*: when a material is extracted from nature, it will eventually become waste.
- *50/50 methods*: supply of and demand for recyclable material are both required for recycling to occur…
- *Circular Footprint Formula*, *price-based substitution*, *price-elasticity approaches*: …but the relative importance of supply and demand will vary between materials.
- *Circular Footprint Formula*, *price-based allocation and price-based substitution*: the more a recycled material loses in quality and economic value, the sooner it will be disposed of and replaced by virgin material.

The results from our hypothetical case illustrate that the choice of method decides what aspects of recycling will be important for the LCA results (Table 4). With *allocation to material losses*, the results are decided by the rate of recycling at the end of product life. This typically gives a strong incentive to design for recycling, and to collection for recycling of waste.

Table 4: How to deal with the allocation problem? Factors important for the results of the calculation.

Method	Recycled content	Recycling rate	Quality	Price	Market mechanisms
Simple cut-off	X	(X)			
Economic cut-off	X	(X)			
Cut-off plus credit	X	X			
Allocation to material losses		X			
Allocation to virgin material use	X				
50/50 methods	X	X			
Quality-adjusted 50/50	X	X	X		
Circular Footprint Formula	X	X	X		X
Price-based allocation	X	X		X	
Price-based substitution	X	X	X	X	
Price-elasticity methods	X	X			X
APOS	X	X		X	

With *allocation to virgin material use*, the results are instead decided by the recycled content in the product. This is likely to give a strong incentive to the use of recycled material. *Cut-off methods* in many cases also give this incentive.

With other methods, the recycled content and recycling rate both affect the results. The results can, in addition, be affected by losses of material quality or economic value, and/or by the mechanisms of the market for recyclable materials; the latter includes the Factor A in the *Circular Footprint Formula* and the own-price elasticity of demand and supply for recyclable material in the *price-elasticity methods*. These methods can give an incentive both to using recycled material, to recycle material after use, and to preserve the quality of the material, but these incentives are weaker and less significant compared to the extreme methods allocation to material losses or to virgin material use.

Criteria for assessing allocation methods

Criteria for what is a “good“ environmental assessment method were presented by Ekvall (2018 and 2020), who defines as a main criterion that environmental assessment methods should lead to overall reduced environmental impact. The identification of such methods is supported by a list of five sub-criteria for methodological choices.

With this list of sub-criteria as a starting point, we developed criteria for good methods for allocation of recycling in LCA. Other published criteria for ”good” recycling allocation methods were collected from the literature. These were used to refine and complement the criteria by Ekvall to be more precisely defined and to fit the context of allocation of recycling. The result is a revised and extended list of criteria. The criteria were also complemented with explanations of how to assess if a specific criterion is fulfilled. This assessment is described in the chapter *Assessment of methods*.

Critical analysis of original criteria

Each criterion in (Ekvall 2018) was analyzed with regard to clarity and logic, by asking the following questions: Is the meaning of the criterion explained in a precise and clear-cut way, without risk for misinterpretation? Are there no logical gaps or inconsistencies in the underlying reasoning leading to the criterion? Is there any form of subjective bias in the criterion? Does anything need to be reformulated in order for the criterion to be applicable specifically to allocation, and not LCA methods in general? The results of the critical analysis are presented in Annex 1.

Literature search

The literature search covered a reasonable but not exhaustive share of peer-reviewed scientific LCA literature published until April 2019. As a first step, articles containing criteria for “good allocation methods” were collected from the project application and from the reference lists of those articles. The ISO LCA standard (ISO 2006) and the Product Environmental Footprint Guide (EC 2013) were also included. Next, journals where the first set of articles were encountered were searched for articles including the search terms “allocation AND recycling“ in the title, keywords, or abstract. In total, the literature search identified 23 publications (Annex 2h).

Many of the articles that were found included descriptions or comparisons of different allocation methods. Very few included explicit criteria for “good” allocation methods. Still, a variety of criteria were identified, some presented as sets of criteria with the aim to cover all important aspects of choice of allocation method, some highlighting only one or two specific aspects. While some criteria are well described and motivated, others seem more arbitrary.

Revised criteria

As a result of the critical analysis and the literature search, the five original criteria were split into 10 more clear-cut revised criteria and reframed for the context of allocation of recycling (Table 5). With each criterion also comes a description of how fulfillment of the criterion can be assessed. Although the aim of these criteria is to make the assessment of allocation methods more transparent and systematic, it is important to note that the assessment still relies to a large extent on subjective judgement.

It is not possible to ascertain if an assessment method actually leads to reduced environmental impact. For this reason, the main criterion from Ekvall (2018) was re-phrased to focus on the incentives towards reduced environmental impact that an allocation method creates. The 11 revised sub-criteria concern either how an allocation method is defined/designed, or how it is perceived by users. The revised criteria are presented in Table 5.

When searching for criteria for “good” allocation methods, a number of aspects also emerged that are not criteria that can be fulfilled or not, but rather important descriptors of normative and fundamentally different perspectives on certain aspects (Table 6). A decision maker’s normative views may lead to different conclusions regarding how the criteria should be interpreted and hence also the question “what is a good recycling allocation method”. Different perspectives can also be more or less appropriate in different decision contexts (product labelling, procurement, national policy, product development, explorative research, corporate strategy…). These normative choices were not integrated in the definitions of the criteria. Instead, they should be discussed and agreed upon before applying the criteria.

Table 5: Main criterion and sub-criteria for good methods for allocation of recycling, based on Ekvall (2018).

Criterion	Description of criterion	Assessment of fulfillment
Main criterion	A good method for allocation of recycling should create incentives for solutions that reduce overall negative environmental impact, or at least per produced functional unit, of product life cycles.	N/A
Easy to use	The allocation method is perceived by the users as being easy to use, in terms of having low level of theoretical complexity. Comment: The perceived "ease of use" depends on the practitioners' knowledge and experience. A higher level of complexity may be acceptable in certain decision contexts, if it leads to results being more "close to reality" and the additional complexity is balanced by better outcomes for decision-making.	The criterion is assessed in a two-step process: Step 1) Preliminary assessment based on expert judgement before pilot-testing, taking into consideration the number of parameters, number of processes that need to be allocated, and qualitative assessment of the complexity of the theoretical basis of the methods. Step 2) For selected methods: update of assessment after experience from pilot testing in case studies by users with varying knowledge, skills and experience of LCA.
Readily available data	Data required to apply the allocation method is readily available from e.g. stakeholders or databases or given as default values as part of the description of the allocation method. Comment: Focus is on actual availability. While *actual* availability of data depends on product category, *perceived* availability of data may depend on knowledge of data sources among users.	The criterion is assessed in a two-step process: Step 1) Preliminary assessment based on expert judgement before pilot-testing, taking into consideration the amount of data/parameters needed in addition to those provided by the method reference. Step 2) For selected methods: update of assessment after experience from pilot testing for different product categories.
Generalizable results	Through its design, the allocation method generates results that apply equally well under different case specific conditions. Comment: Generalizable results can be for instance simple rules of thumb. There is always a trade-off between precision relating to a specific case and generalizability, where one or the other may be more important in different decision contexts.	The criterion is assessed by checking if case specific parameters in the method will prevent the results from being applicable to similar cases in other contexts.
Reflects environmentally decisive system characteristics	The allocation method accounts for environmentally decisive processes and flows, i.e., aspects of the recycling that are environmentally important. Comment: The environmentally decisive processes and flows are those that are expected by an informed expert to play a key role in determining the environmental impact of recycling. The interpretation of this criterion is affected by choice of causality model (Table 6), as the calculated impact can be either effect oriented or cause oriented. In this study, an effect-oriented view was applied when assessing the fulfilment of this criterion.	The criterion is assessed by checking that the method incorporates the following factors to the extent that an informed expert expects them to determine the environmental consequences of recycling: - differentiates between virgin and recycled material, - differentiates between material recycling, energy recovery, and disposal, - differentiates between different fates of recovered resources, and - differentiates between material

		flows with different quality.
Life cycle scope	The allocation method should facilitate or at least allow for a life cycle approach to be maintained in the system model. <u>Comment:</u> The method is designed such that the system model can include the full product life cycle without gaps, while double counting of activities or part of activities is avoided. This allows the LCAs of different products using the same material to generate additive results. The product life cycle is in this report (see beginning of in the chapter *Methods for modeling recycling*) defined as the system of activities from the production of virgin or secondary material, through manufacturing processes and use, to the waste management of residual products and materials. Credits, for example after end-of-life, are not included in the life cycle.	The criterion is assessed by checking the following: 1) All stages of the product life cycle are included by design of the method: - upstream processes of virgin material as well as any recycled content - downstream processes, including end-of-life treatment processes 2) Double counting is avoided. 3) Symmetry of material flows is ensured, i.e. it is assigned the same burdens when leaving one life cycle as when entering the subsequent life cycle.
Explicit, justified, and evaluated	The allocation method is documented explicitly, justified, and evaluated (through sensitivity analysis or scenario analysis). <u>Comment:</u> This criterion refers to the standard or reference describing the method, not the method itself.	The criterion is assessed by checking if the method is documented according to any international standard or other reference guide on LCA and if it has been evaluated through practical or theoretical application.
Comprehendible	The allocation method is documented with clear structure and terminology in a way that can be understood by the expected users.	The criterion is assessed in a two-step process: Step 1) Preliminary assessment based on expert judgement before pilot-testing, taking into consideration if the method is well explained. Step 2) For selected methods: update of assessment after experience from pilot testing in the case studies.
Relevant to decision-makers	The allocation method is designed in such a way that decision-makers can influence the parameters that determine the impacts calculated through allocation, and that it is adjusted to the specific knowledge needs of affected stakeholders.	The criterion is assessed by evaluating if at least one key parameter of the method can be influenced by key stakeholders in the specific decision context.
Legitimate	The allocation method is perceived by the users as being well-anchored and fair.	The criterion is assessed by evaluating if the method development process is perceived by key stakeholders in a decision context as well-anchored and that there is consensus among key stakeholders for the specific decision context concerning the fair distribution of burdens and benefits in a product cascade system.
Reproducible	The allocation method leaves no or little room for the user to adjust its design or data, so that the method gives reproducible results and does not lend itself to misuse.	The criterion is assessed by evaluating if detailed and unambiguous method and data guidelines exist that ensure that the method is used in a reproducible manner by different users.

Table 6: Normative descriptors of allocation methods, to be considered and agreed up on for every decision context. Derived from the literature search (see Annex 2).

Normative descriptors	Explanation
Use of criteria Yes, apply criteria *OR* No, allow plurality	Allocation modeling involves value judgements and subjectivity. Allowing for plurality, instead of trying to reach consensus on modeling criteria, may therefore be a better approach (Frischknecht 2006). <u>Comment:</u> The value of applying criteria is taken as a given starting point in this study. However, application of criteria for assessment of different allocation methods only serve to clarify their strengths and weaknesses. The goal of this project was to facilitate a debate among Swedish actors on how recycling should be modelled in LCA and similar assessments, not to single out one single method as a best approach.
Causality model Effect-oriented *OR* Cause-oriented	Allocation modeling can be based on either effect-oriented (consequential) or cause-oriented (attributional) causality (Ekvall & Tillman 1997). Effect-oriented modeling of a recycling process focusses on the consequences of recycling, i.e., on the avoided waste disposal and virgin material production. This fits in a consequential LCA, which aims to describe the consequences of the production and use of the product, or of changes made in the life cycle, whether they occur inside or beyond the boundaries of the life cycle. Cause-oriented modeling of a recycling process focusses on the causes of the process and, hence, its environmental impacts. The recycling process might be driven both by a need to treat a waste material and by the demand for new, recycled material. If so, the emissions of the recycling process are partitioned between the two functions in proportion to how much they contribute to driving the process. This fits in an attributional LCA, which aims to quantify the emissions and resource demand of the processes in the life cycle. See also Table 3. <u>Comment:</u> When the overall aim is to reduce overall environmental impact, the choice of causality model will depend on a subjective view of what perspective contributes to reduced overall environmental impact in a specific decision context. This choice will determine how the criterion “Reflects environmentally decisive system characteristics” is interpreted, because the decisive system characteristics can differ between these two perspectives. In this study, an effect-oriented view was applied when assessing the fulfilment of this criterion.
Sustainability model Strong sustainability modeling approach *OR* Weak sustainability modeling approach	Allocation modeling can be based on either strong sustainability (where human capital and natural capital are complementary but not interchangeable) or weak sustainability (where human capital can substitute natural capital) (Frischknecht 2010). <u>Comment:</u> The weak sustainability model allows environmental credits of possible future recycling to be accounted for. The strong sustainability model requires that burdens be accounted for when they arise. In this study, both perspectives were allowed when assessing fulfillment of criteria.
Risk attitude Risk-averse attitude *OR* Risk-seeking attitude	Allocation modeling can be based on either a risk-averse or a risk-tolerant approach. A risk-tolerant approach deliberately accepts the risk associated with future uncertainty of markets and behavior. A risk-averse approach does not accept the risk associated with future uncertainty of markets and behavior. (Frischknecht 2010) <u>Comment:</u> For instance, the Simple cut-off allocation model adheres to a risk averse attitude, as the allocation model does not require any assumptions about future recycling practices. The risk attitude of the decision maker may influence the interpretation of the criteria “Reflects environmentally decisive system characteristics” and “Life cycle scope”. In this study, both perspectives were allowed when assessing fulfillment of criteria.
Consistency in allocation principle at system level Required *OR* Not required	Consistency of allocation principle among recycling, energy recovery and co-production can be a requirement at system level (Schrijvers et al. 2016b). <u>Comment:</u> If this is set as a requirement, then the same allocation principle must be applied at the end of the product life as for other multi-functional processes within the modelled system. For instance, simple cut-off would be disqualified if economic allocation is applied for co-product allocation in the production system. In this study, as the focus is only on recycling allocation methods, no decision had to be made for this aspect.

Assessment of methods

This chapter presents an assessment of the methods described in the chapter *Methods for modeling recycling*, applying the refined criteria described in the chapter *Criteria for assessing allocation methods*. A summary of the results is available in Figure 32, with more detailed descriptions and justifications in the following sub-sections.

The assessment is based on to what extent the criteria were fulfilled at the time of writing the present report (from May 2019 to May 2020). The fulfilment of some criteria, such as “easy to use”, “readily available data”, “explicit, justified, and evaluated” and “legitimate”, may, however, improve over time. For example, ease of use and availability of data may be improved if a method is implemented in LCA software, and the justification and legitimation of a method may be improved by international consensus processes and implementation into standards. That the fulfilment of some criteria can be improved over time, whereas the fulfilment of other criteria instead are inherent properties of the methods, have not been accounted for in the assessment.

As 12 methods were assessed based on 10 criteria, 120 individual assessments had to be done. To make such an extensive assessment feasible and communicable, the outcome is reported with colour-coded smileys in Figure 32 (e.g., happy green smiley = criteria fulfilled) and rather brief justifications in the subsequent sub-chapters.

The assessment is an update of a previous assessment done in the project. The original assessment was done by Kristian Jelse and the updated and final one by Gustav Sandin (both at IVL Swedish Environmental Research Institute). In the updating process, experiences from the case study reports (Annexes 3-9) were considered along with adjustments made to the criteria and their definitions during the duration of the project. As several of the case studies did not apply the allocation methods using some sort of price as a basis for allocation, nor the allocation at the point of substitution (APOS) method, the assessments of these methods are based on less evidence compared to the assessments of the other methods.

Finally, it is important to stress that an exercise of this kind is inherently value-laden, and other persons conducting a similar assessment will probably report other results.

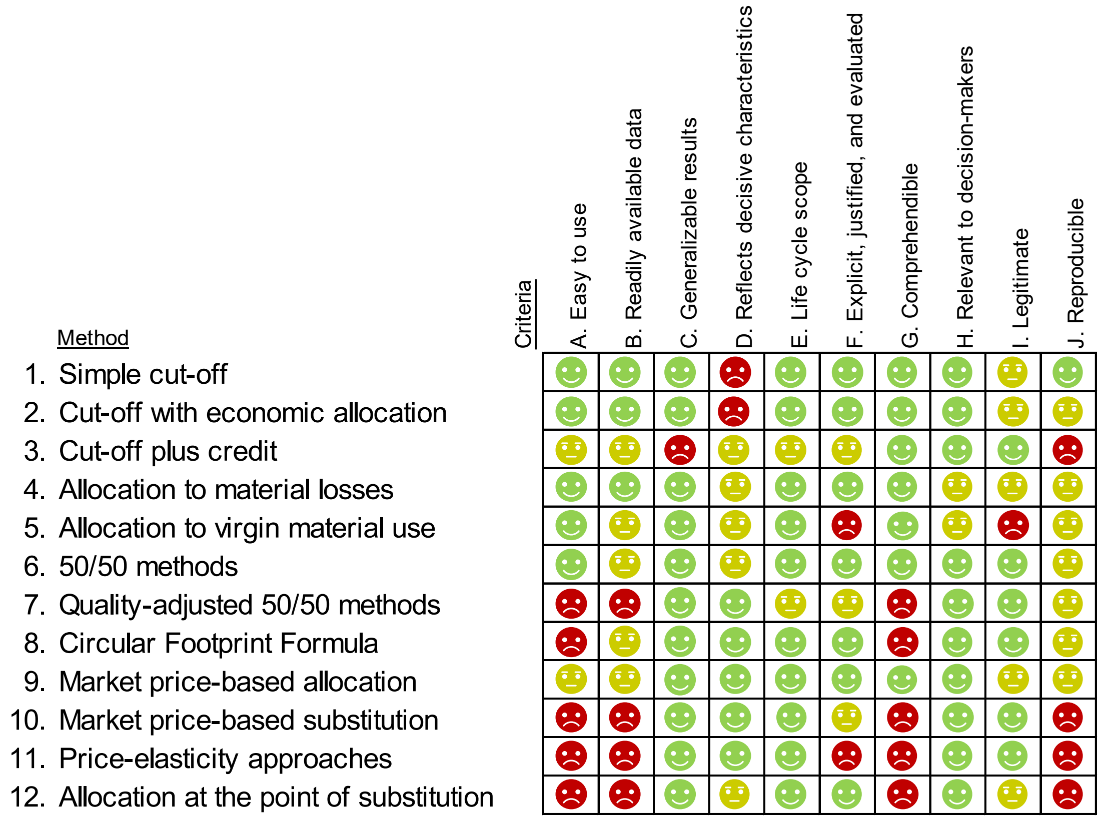

Figure 32: Summary of assessment of the methods by two IVL researchers applying the refined criteria. Green = criteria fulfilled. Yellow = criteria partly fulfilled. Red = criteria not fulfilled.

Simple cut-off

Easy to use

The method was assessed to fulfil this criterion as it is probably the easiest approach to model recycling. Each product is assigned the environmental burdens of the processes in the life cycle of that product and no information about processes beyond the life cycle is needed. The only challenge is to define the boundary between the life cycles: should this boundary be before, within, or after the recycling of the material?

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed to be fulfilled as the method does not require any environmental data on processes beyond the product life cycle. For example, data on virgin production are not needed if no virgin material is used and data on disposal are not needed if no disposal is used. Quality parameters or substitution factors are also not needed.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed not to be fulfilled. The method differentiates between virgin and recycled material, and between different fate of recovered resources (e.g., recycling, energy recovery, and disposal), but not to the extent that an informed expert may expect when determining the environmental consequences of recycling. Furthermore, the method does not differentiate between different qualities of materials.

Life cycle scope

This criterion was assessed to be fulfilled. As all life-cycle stages are included, and as the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is a simple method and is recommended by multiple guidelines.

Comprehendible

The method was assessed to fulfil this criterion. Among the methods assessed, it is the easiest to explain and to illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

Legitimate

The method was assessed to partially fulfil this criterion as the allocation of virgin material production to the first product life cycle, and the allocation of disposal to the final user, may be perceived as unfair by some stakeholders. The method is recommended by multiple guidelines, giving it some additional legitimacy.

Reproducible

The method was assessed to fulfil this criterion as the method is easily understood and has a high degree of transparency, which should make the results easily reproducible.

Cut-off with economic allocation

Easy to use

This method was assessed to fulfil this criterion as it is only somewhat more complex to apply compared to the simple cut-off method. The method requires no environmental data on processes beyond the product life cycle and no information related to quality of materials. Economic allocation of the recycling process means that data on prices must be collected or estimated.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed to be fulfilled as the method requires no environmental data on processes beyond the product life cycle, for example data on virgin production not needed if no virgin material is used and data on disposal not needed if no disposal is used within the product life cycle.

Compared to data collection for the simple cut off method, economic allocation means that data on prices must be collected or estimated, but this was assessed to be a minor addition.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to not be fulfilled. The method differentiates between virgin and recycled material, different fate of recovered resources, and different quality of material received from, or sent to, recycling (indirectly through the economic allocation of the recycling processes). However, this differentiation is not to an extent that an informed expert may expect when determining the environmental consequences of recycling beyond the product life cycle.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is a simple method and is recommended by one identified guide. What economic value to use for the allocation is, however, not explicit – but this was assessed to be a minor shortcoming in terms of this criterion.

Comprehendible

The method was assessed to fulfil this criterion as it is easy to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

Legitimate

The method was assessed to partially fulfil this criterion as the allocation of virgin material production only to the first product, and the allocation of disposal to the final user, may be perceived as somewhat unfair by some stakeholders. The method is only recommended by one identified guide.

Reproducible

The method was assessed to partially fulfil this criterion. For reproducible results, economic data on allocation needs to be transparently reported. Users of recycled material and users sending material to recycling may make different assumptions about the allocation factor to use. If so, some environmental impact may not be attributed to any product life cycle.

Cut-off plus credit

Easy to use

This criterion was assessed to be partially fulfilled as the method is somewhat more complex than the two previously described cut-off methods. In addition to the processes in the product life cycle, a substituted process will have to be defined that is beyond the life cycle. A value-correction factor will also have to be defined.

The assessment of ease of use was confirmed in the case studies.

Readily available data

The criterion was assessed to be partially fulfilled as the method requires more data than the simple cut-off method: a credit for virgin production and a value-correction factor. The standards in which is the method is recommended do not define functional equivalence or explain how the value-correction factor should be calculated.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

In contrast with all other methods, this criterion was assessed not to be fulfilled for this method as Module D treats downstream and upstream recycling differently.

Reflects decisive characteristics

This criterion was assessed to be partially fulfilled. The method differentiates between virgin and recycled material, but not to the extent that an informed expert may expect when determining the environmental consequences of recycling. However, the method differentiates between the fate of recovered resources, and between different quality of material sent to recycling (as they translate to different credits, to an extent an informed expert may expect when determining the environmental consequences of recycling.

Life cycle scope

This criterion was assessed to be partially fulfilled. All life-cycle stages are included, but the method is asymmetric as long as Module D is applied on net outflows of recyclable materials only. The results generated with this approach are also not additive. Results from different modules should not be aggregated and if they were, part of the recycling activities would be counted twice (as part of Module D in the upstream product and part of Module A in the subsequent product).

Explicit, justified, and evaluated

The method was assessed to partially fulfil this criterion as it is prescribed by and described the European standard EN 15804, but the standard does not define functional equivalence or explain how the value-correction factor should be calculated.

Comprehendible

The method was assessed to fulfil this criterion as it is easy to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

Legitimate

The method was assessed to fulfil this criterion even if the allocation of virgin material production to the first product life cycle may be perceived as somewhat unfair by some stakeholders. The method is prescribed by EN 15804 and is used by many companies in EPDs, which increases legitimacy greatly.

Reproducible

The method was assessed to not fulfil this criterion. The standards do not define functional equivalence or explain how the value-correction factor should be calculated. Results are thus not likely to be reproducible or consistent across studies.

Allocation to material losses

Easy to use

This method was assessed to fulfil this criterion. No processes need to be shared across the product life cycles as virgin material production is simply attributed to the life cycle where the material loss occurs.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed to be fulfilled. For the first two example life cycles (E_1 and E_2), this method relies only on readily available data. In the case of E_3, the method is likely to require data on virgin material production even when the product contains no virgin material (cf. Product 3 in our case). However, global or regional average data on virgin material production are in most cases easy to find in databases.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to be partially fulfilled. It does not differentiate between virgin and recycled material and different quality of material. It does, however, differentiate between different fate of recovered resources, and whether it goes to material recycling, energy recovery or disposal, and it does so to an extent an informed expert may expect when determining the environmental consequences of recycling (as it gives a strong incentive to produce recyclable products).

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is a simple method and is recommended by multiple guidelines, including an ISO standard.

Comprehendible

The method was assessed to fulfil this criterion as it is easy to explain and illustrate.

Relevant

The method was assessed to partially fulfil this criterion. The share of material sent to recycling affects the results. However, the method gives no incentive to use recycled material. The share of recycled material in the product (R1) does not affect the results at all.

Legitimate

The method was assessed to partially fulfil this criterion as different stakeholders are likely to perceive the method as fair or not depending on whether they have to take the full burden of virgin production or disposal. The method is (for certain cases) recommended by multiple guidelines, including ISO TR 14049, PAS 2050 and GHG Protocol, which increase legitimacy.

Reproducible

The method was assessed to partially fulfil this criterion.

Using this method, different studies of the same product may use different input data to model virgin material production. This makes the method less reproducible.

Moreover, unless subsequent systems utilizing the same material are consistently modelled, the environmental impacts of virgin material production might be double-counted or partly unaccounted for.

Allocation to virgin material use

Easy to use

This method was assessed to fulfil this criterion. No processes need to be shared across the product life cycles as disposal is simply attributed to the life cycle where virgin material is used.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed to be partly fulfilled. For two of the example product life cycles (E_2 and E_3), this method relies only on readily-available data. In the case of E_1, the LCA is likely to require data on disposal even when the product is fully recycled (cf. Product 1 in our case). Data of final disposal of a certain material is generally more difficult to find when outside the product system, compared to finding data of virgin production occurring outside the product system. This is because material disposal may depend on, and be difficult to separate from, product disposal – and the final product may be unknown in relation to E1. Also, disposal can differ considerably between countries and regions, and for long-lived products (e.g. construction products) it occurs typically 50-100 years into the future, adding to the uncertainty of disposal practices.

Finding data for this method, and its above-discussed reliance on disposal data, was not acknowledged as being an issue in any of the case study reports. Based solely on the reports, the assessment could instead have been "fulfilled".

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to be partially fulfilled. The method does not differentiate between different fate of recovered resources (whether they go to material recycling, energy recovery or disposal), or different quality of material. However, the method does differentiate between virgin and recycled material, and it does so to an extent an informed expert may expect when determining the environmental consequences of recycling (as it gives a strong incentive to the use of recycled material).

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The criterion was assessed not to be fulfilled. The method was discussed at an early stage by Östermark & Rydberg (1995) but is according to our knowledge recommended by any standard, guideline or similar document.

Comprehendible

The method was assessed to fulfil this criterion as it is easy to explain and illustrate.

Relevant

The method was assessed to partially fulfil this criterion. The share of recycled material use affects the results, but the share of material sent to recycling after use does not affect the results.

Legitimate

The method was assessed to not fulfil this criterion as different stakeholders are likely to perceive the method as fair or not depending on whether or not they have to take the full burden or virgin production and disposal.

In addition, the method was only discussed at an early stage by Östermark & Rydberg (1995). It is according to our knowledge recommended by any standard, guideline or similar document.

Reproducible

The method was assessed to partially fulfil this criterion.

Different LCAs of the same product may use different input data to model the waste disposal. This makes the studies less reproducible.

Moreover, unless subsequent systems utilizing the same material are consistently modelled, the environmental impacts of the waste disposal might be double-counted or partly unaccounted for.

50/50 methods

Easy to use

This criterion was assessed to be fulfilled as this method is fairly easy to use and understand. These is no need for data on quality or price, and no need for system expansion or issues related to “functional equivalence” or similar. There are potentially some shortcomings related to ease of use (see next criteria), but these are regarded as minor in terms of the assessment of ease of use.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This method was assessed to be partially fulfilled. Compared to the previous two methods, it is only for E2 that all data are readily available. For E1 and E3, additional collection of data on virgin material use or disposal are needed for the product life cycles where no virgin material is used or no disposal occurs, respectively. Particularly, this may pose a problem for disposal data, see reasoning in previous chapter.

Finding data for this method, and its above-discussed reliance on disposal data outside the product system, was not acknowledged as being an issue in any of the case study reports. Based solely on the reports, the assessment could instead have been "fulfilled".

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to be partially fulfilled. It does differentiate between virgin and recycled material and different fate of the recovered material, and it does so to an extent that an informed expert may expect when determining the environmental consequences of recycling (as supply of and demand for recyclable material are both required for recycling to occur). However, the method does not differentiate between different quality of material.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is included in different guidelines, with some variations.

Comprehendible

The method was assessed to fulfil this criterion as it is rather easy to explain.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

Legitimate

The method was assessed to fulfil this criterion as it is likely to be perceived as fair by different stakeholders when the burdens are shared 50/50.

Reproducible

The method was assessed to partially fulfil this criterion. Unless subsequent systems utilizing the same material are consistently modelled, the environmental impacts of virgin material production, recycling and waste disposal might be double-counted or partly unaccounted for.

Quality-adjusted 50/50 methods

Easy to use

This criterion was assessed to not be fulfilled. In each study, a factor reflecting the degradation of material quality must be defined and calculated. How this is to be done is not sufficiently described in guiding documents.

Several of the case study reports highlighted this method as being difficult to use, thus confirming this assessment.

Readily available data

This criterion was assessed not to be fulfilled. For all three products in the examples of previous chapters (E_1, E_2, E_3), data are needed beyond the normal product life cycle. Moreover, in addition to the data requirements of the 50/50 method, a factor reflecting the degradation of material quality needs to be defined and calculated. How this is to be done is often not sufficiently described in guiding documents.

Several of the case study reports confirmed this method as being difficult to find data for.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to be fulfilled. It does differentiate between virgin and recycled material, different quality of material, and different fate of the recovered material, and it does so to an extent that an informed expert may expect when determining the environmental consequences of recycling (as supply of and demand for recyclable material are both required for recycling to occur).

The method thus promotes the use of recycled material and sending material to recycling, and promotes maintaining the quality of recycled material.

Life cycle scope

This criterion was assessed to be partially fulfilled. All life-cycle stages are included, but the results are not additive, as the environmental value of recycled material leaving a product system may be different from the environmental value assigned to the recycled material when it enters the next product system.

Explicit, justified, and evaluated

The method was assessed to partially fulfil this criterion, as it is included in different guidelines, with some variations. Some version of the method (UBA) require interpretation to be used, however.

Comprehendible

The method was assessed to not fulfil this criterion as it is rather complex to explain and illustrate. This was confirmed by several of the case study reports.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

In addition, maintaining quality of the material sent to recycling also influences the results.

Legitimate

The method was assessed to fulfil this criterion as it is likely to be perceived as fair by different stakeholders as the burdens are shared in a quality-dependent way.

The method is also included in different guidelines, with some variations. It was recommended in an early version of the PEF guidelines, which now instead recommends the Circular Footprint Formula CFF, which could reduce legitimacy.

Reproducible

The method was assessed to partially fulfil this criterion. All environmental impact may not be accounted for unless different studies are based on consistent modeling, for example in terms of the definition of the factor reflecting material quality.

Circular Footprint Formula

Easy to use

This criterion was assessed not to be fulfilled. The method is more complex to apply than the methods above, partly because it distinguishes between the virgin production of the investigated material (E_V) and the virgin production avoided through recycling (E^*_V). The main challenge, however, is to quantify the quality of the recycled materials.

The assessment of ease of use was generally confirmed in the case studies, although some participants in the case studies expressed that the method is not difficult to use if the method and the data it relies on is integrated in software and databases. The same can, however, be argued for any method, and this assessment is based on the ease of use at the time of writing the present report.

Readily available data

This criterion was assessed to be partially fulfilled. The method requires more data than any of the above described methods, but for some materials/product categories data are provided as part of the PEF method guide and are thus readily available for the LCA practitioner. As reported in the case study reports, some of the other data can, however, be difficult to obtain, and for some materials/product categories default data are not available. Also, some of the default values provided in the PEF method guide were deemed to be questionable.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context. Factor A changes depending on material but is consistent for the same material.

Reflects decisive characteristics

This criterion was assessed to be fulfilled. The criterion differentiates between virgin and recycled material, between different fate of recovered resources and the different quality of material, and it does so to an extent that an informed expert may expect when determining the environmental consequences of recycling. The method thus promotes the use of recycled material and sending material to recycling and promotes maintaining the quality of recycled material.

The strength of all these incentives varies between materials and depends on Factor A as well as on the quality losses in the use and recycling of the material. As described in the chapter *Methods for modeling recycling*, the incentive to recycle material after use can disappear if the disposal processes bring a net environmental benefit, which can happen even when a high recycling rate is environmentally beneficial at the societal level

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion. It was developed in a five-year pilot project based on a draft methodology issued by the European Commission, including multiple workshops involving many types of stakeholders. The process and the resulting method are well-documented.

Comprehendible

The method was assessed to not fulfil this criterion as it is complex to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results. In addition, maintaining quality of the material sent to recycling also influences the results.

Legitimate

The method was assessed to fulfil this criterion as it is likely to be perceived as fair by different stakeholders as the burdens are shared in a quality-dependent way.

Legitimacy is strengthened by the fact that it was developed in a broad consensus process: a five-year pilot project led by the European Commission including multiple workshops involving many types of stakeholders

Reproducible

The method was assessed to partially fulfil this criterion. As it difficult to use, and data can be difficult to find, there is a risk for errors, impeding reproducibility. On the other hand, the various factors are more well-defined, and the guidance more comprehensive, compared to many of the other methods, which increases reproducibility.

Market price-based allocation

Easy to use

This criterion was assessed to be partially fulfilled as the method is more straight-forward than the quality-adjusted 50/50, CFF, market-based substitution, price-elasticity and APOS methods, but more complex than the 50/50 and cut-off methods.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed to partially be fulfilled. For E_2, data are readily available, but E_1 and E_3 rely on data on the ratio between the global market value of scrap material or recycled material, and the global market value of virgin material. For E_3, data on virgin production is needed even if this is outside of the product life cycle.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context. Factor A changes depending on material but is consistent for the same material.

Reflects decisive characteristics

This criterion was assessed to be fulfilled. The criterion differentiates between virgin and recycled material, between different fate of recovered resources, and the different quality of material, and it does so to an extent an informed expert may expect when determining the environmental consequences of recycling. The method does this by accounting for economic losses: the more the recycled material loses in economic value, the sooner it will be disposed of and replaced by virgin material.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is used in ISO 14067.

Comprehendible

The method was assessed to fulfil this criterion as it is rather easy to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used and share of material sent to recycling may influence the results.

Legitimate

The method was assessed to partially fulfil this criterion as it is likely perceived a relatively fair by some stakeholders, but actors late in the material-use chain, when the material quality has deteriorated, may perceive their allocated burden as being unproportionately large. The legitimacy may depend, for example, the choice of Factor A.

Reproducible

The method was assessed to partially fulfil this criterion. Unless subsequent systems utilizing the same material are consistently modelled, for example in terms of the choice of Factor A, all environmental impact may not be accounted for.

Market price-based substitution

Easy to use

This criterion was assessed not to be fulfilled. This method is even more complex to apply than the Circular Footprint Formula as it includes more variables and requires more data.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed not to be fulfilled. The method requires more data than the Circular Footprint Formula, but in contrast those data are not known to be available in any reference guide. Data are needed beyond the life cycle for all three example product life cycles (E_1, E_2, E_3).

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context. Factor A changes depending on material but is consistent for the same material.

Reflects decisive characteristics

This criterion was assessed to be fulfilled. The criterion differentiates between virgin and recycled material, between material recycling, energy recovery, and disposal, between different fate of recovered resources and the different quality of material, and it does so to an extent an informed expert may expect when determining the environmental consequences of recycling. Thus, the method gives a clear incentive to recycle metals and other materials that have a similar quality and value after recycling as the virgin material. However, similar to the Circular Footprint Formula, this approach can eliminate the incentive to recycle low-grade material after use if the disposal processes bring a net environmental benefit, even when a high recycling rate is environmentally beneficial at the societal level.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to partially fulfil this criterion as it is included in one guide.

Comprehendible

The method was assessed to not fulfil this criterion as it is complex to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used, the share of material sent to recycling, and the quality losses, may influence the results.

Legitimate

The method was assessed to fulfil this criterion as it is likely to be perceived as fair by different stakeholders.

Reproducible

The method was assessed to not fulfil this criterion, as it difficult to use, data can be difficult to find, and compared to, for example, CCF, factors are not as well-defined and less default values are available in guidance documents. Choices for what factors to use must thus be defined in each study, and there is a risk for errors, impeding reproducibility.

Price elasticity methods

Easy to use

This criterion was assessed not to be fulfilled. Allocation based on price elasticities is less complex than the CFF or the market-price substitution method of Schrijvers et al. (2016a) in the sense that it includes fewer parameters. However, up-to-date estimates of the price elasticity for recyclable materials are scarce. This makes the approach difficult to apply in practice, at least with accuracy.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed not to be fulfilled. Up-to-date estimates of the price elasticity for recyclable materials are scarce. This makes the approach difficult to apply in practice, at least with accuracy.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context. The Factor η changes depending on material but is consistent for the same material.

Reflects decisive characteristics

This criterion was assessed to be fulfilled. The criterion differentiates between virgin and recycled material, between material recycling, energy recovery, and disposal, between different fate of recovered resources, and between different quality of materials, and it does so to an extent that an informed expert may expect when determining the environmental consequences of recycling.

Similar to several other methods, the incentives created by this method will vary between materials. When the supply and demand is equally elastic, such as indicated by the default values for glass bottles, this approach will typically give incentives to the use of recycled material as well as to recycling after use. An exception might occur when final disposal brings significant net benefits for the environment.

When the supply of recyclable material is much more elastic than the demand, such as indicated by the default values for plastic bottles, this approach gives a clear incentive to the use of recycled material but little incentive to recycling after use, particularly when the final disposal is good for the environment.
The method also promotes maintaining the quality of recycled material via the Factor S.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The criterion was assessed not to be fulfilled. The method was proposed in a research paper by Ekvall (2000) but is not recommended by any guidelines.

Comprehendible

The method was assessed to not fulfil this criterion as it is complex to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used, the share of material sent to recycling, and the quality losses, may influence the results.

Legitimate

The method was assessed to fulfil this criterion as it is likely perceived a relatively fair by different stakeholders. The legitimacy may, however, depend on the choice of Factor A.

Reproducible

The method was assessed to not fulfil this criterion as there are many variables and a large degree of freedom in each study, as there are no default values available.

Allocation at the point of substitution

Easy to use

This method was assessed to not fulfil this criterion due to its complexity. For example, input materials can origin from many different products, with various and differing production and use phases, which is unpractical and difficult to model.

The assessment of ease of use was confirmed in the case studies.

Readily available data

This criterion was assessed not to be fulfilled. The allocated burdens include burdens from virgin material production, but also from the manufacturing processes and the use phase of the product that is recycled after use. This means that the recycled material can carry seemingly unrelated environmental burdens, for which data can be difficult to obtain.

The assessment of availability of data was confirmed in the case studies.

Generalizable results

This criterion was assessed to be fulfilled as the method does not change depending on context.

Reflects decisive characteristics

This criterion was assessed to be partially fulfilled.

The criterion differentiates between virgin and recycled material, different fate of recovered resources, and different quality of materials. As the method accounts for processes beyond the product life cycle – although not beyond the material life cycle – it can be argued that the above differentiation is made to an extent that an informed expert may expect when determining the environmental consequences of recycling.

However, as was described in the chapter *Methods for modeling recycling*, in this report’s interpretation of the method, it assigns seemingly unrelated manufacturing and use processes from the previous product life cycle, to the product using the recycled material. If the manufacturing and use of a product have much larger environmental impacts compared to the materials production, the recycled material from this product can carry more environmental burdens than virgin material. This means that the method can give producers an incentive to choose virgin material over recycled material, even when a high rate of recycling is environmentally beneficial for the society. These mechanisms of the method are not in line with what an expert may except in terms of the environmental consequences of recycling, and this criterion can thus not be assessed to be completely fulfilled.

Life cycle scope

This criterion was assessed to be fulfilled. All life-cycle stages are included, and the symmetry of material flows is ensured.

Explicit, justified, and evaluated

The method was assessed to fulfil this criterion as it is documented in the methodology guidelines for the Ecoinvent database. Its implementation in the Ecoinvent database also means that it is most likely widely used.

Comprehendible

The method was assessed to not fulfil this criterion as it is complex to explain and illustrate.

Relevant

The method was assessed to fulfil this criterion as the share of recycled material used, the share of material sent to recycling, and the quality losses, may influence the results.

Legitimate

The method was assessed to partially fulfil this criterion as impacts that could be perceived as being unrelated to the studied product are attributed to it. The method is included in the Ecoinvent database, however, and thus widely available as an option to LCA practitioners.

Reproducible

The method was assessed to not fulfil this criterion as there are many variables and a large degree of freedom in each study, as there are no default values available. Particularly, defining and modeling production and use phases of recycled input materials depends on each practitioner, which impedes reproducibility.

Debating the methods

This chapter presents the outcome of discussions on methods among the project partners. Different approaches to modeling recycling might be appropriate depending on the context of the LCA. For this reason, the discussion was initially structured in three application areas:

- LCAs for policy purposes
- LCAs for external communication
- LCAs for internal use in companies

As evident from the text below, it might be useful or even necessary to distinguish between different applications within each of these application areas. There are also overlaps between them. For example, Environmental Product Declarations (EPDs) is an application of LCA for external communication but also a tool used in green public procurement, which is a policy instrument.

LCAs for policy purposes

When debating the methods, it seems fruitful to distinguish between two different types of application in the policy area:

A. Pre-policy: LCAs that are carried out before the policy decision and generate part of the basis for policy decisions, and

B. Intra-policy: LCAs that are carried out after the policy decision, because the policy requires actors to produce LCAs.

The former is well established in, for example, the development of extended producer responsibility (EPR) in Scandinavian waste-management policy. Several LCAs and life-cycle based cost-benefit analyses have been commissioned by national authorities (e.g., Tillman et al. 1992, Finnveden et al. 1994, Granath & Strömdahl 1994, Westin & Klöfver 1998, Radetzki 1999, Frees et al. 2005) and other actors (e.g., Baumann et al. 1992 & 1993) to provide basis for decisions on or assessments of existing EPR regulations. In this application, it is vital that the LCA conveys the knowledge needed for the policy decision. No general and objective recommendation can be made regarding what specific methods to use in the LCA, but methodological decisions should ideally be made in dialogue with policymakers and stakeholders.

A method could be selected to reflect the logic or assumptions behind a specific policy initiative. For example, *allocation to material losses* reflects the view that collection that materials lost from the technological system must be replaced by virgin materials. This view is consistent with EPR programmes that focus on increased collection and recycling of used materials.

On the other hand, a method can be selected to challenge the assumptions and broaden the view of policymakers. *Allocation to virgin material use* and *50/50 methods* point at the risk of the effectiveness of EPR being reduced because of lack of demand for recycled material. The *CFF* and *price-elasticity* methods, among others, point at the fact that the effectiveness of an EPR can vary between materials.

The LCA practitioner can also apply several different methods in parallel and clearly communicate what can be learnt from the different approaches and results. This makes the study meet the requirement in ISO 14044 to perform a sensitivity analysis with different applicable allocation procedures to illustrate their effects on LCA results.

Studies carried out as a consequence of policy decisions, i.e., intra-policy LCAs, include studies that allow for environmental comparisons of products to be made as a basis for green public procurement – for example EPDs. They also include calculations made to demonstrate that a product fulfills specific environmental requirements – for example, the carbon footprints calculated in the context of the EU Renewable Energy Directive. In this policy context, it is essential that the results from different producers are comparable. This requires that the LCA approach be well-defined, clear and robust. The International EPD System chose the *simple cut-off* approach in an explicit attempt to create a method for these purposes. The *Circular Footprint Formula (CFF)* in the EU framework for Product Environmental Footprints (PEF) was developed as another candidate; the European Commission made the approach more robust by providing default data on Factor A and the quality of important materials (EC 2020). Several other approaches can be specified at the same level of detail, making them just as robust as the *CFF*. Hence, a broad range of methods can be used in intra-policy applications as long as the policy specifies the method in detail.

The two types of applications are connected. If an LCA used as basis for a policy-decision (Type A; pre-policy) finds that specific processes and aspects are environmentally important, these should be accounted for in LCAs resulting from the policy-decision (Type B; intra-policy). Example: if the pre-policy LCA finds that post-consumer recycling of material is crucial because it reduces virgin material production, the avoided virgin material production should also be included in the intra-policy LCAs. This makes the *simple cut-off* a poor approach, because it does not include avoided material production. Most other methods are better in this respect and context.

On the other hand, when products with a very long service life (e.g., buildings and infrastructure) are produced, the actual recycling rate and benefits of recycling are uncertain. The waste-management systems and production processes far into the future are unknown. Because of this uncertainty, one position among the project partners is that it might not seem fair to give a benefit for avoided virgin material production to buildings and infrastructure in green procurement. This would disqualify consequential approaches that account for avoided production of material displaced through recycling (e.g., CFF) and be an argument for the *simple cut-off*. Another position among the project partners is that regardless of the uncertainty, green procurement probably has to account for whether or not a product can be repaired, reused or recycled.

A common way to deal with, or to avoid, the large uncertainties in the far future in LCA is to disregard changes over time and model the waste management with current input data, as if it took place today. This allows for the application of consequential approaches in LCAs of products with long service-life. However, the interpretation of the results should account for the fact that the LCA does not account for possibly large changes over time.

When the avoided virgin material production is highly uncertain but still important for the LCA results, a double approach might also be applied that presents two sets of results from the LCA: one without the credit for avoided virgin-material production, and one with this credit. This resembles the *cut-off-plus credit* method specified in the standards for EPDs of construction products.

Regardless of policy-context, it is an advantage if the LCA accounts for the varying market conditions for recycling of different materials. The more complex methods (*CFF*, *price-based allocation* and *substitution*, the *price elasticity approaches* and *allocation at the point of substitution*) attempt to do this within a single methodological framework. Further analysis of the mechanisms of material markets is required to decide what attempt is the most accurate.

LCAs for external communication

The discussion of methods might also benefit from distinguishing between different types of external communication:

A. Using standardized formats: EPDs, PEFs, etc.

B. Other purposes, including:
   - development of standardized formats,
   - tailor-made comparative assertions, and
   - information on the life cycle and its impacts

Standardized formats might be used in response to requirements from policy instruments such as green public procurement, the Renewable Energy Directive, etc. They can also be used for communication with business-to-business customers in general. When applying a standardized format, the rules of this format stipulate what method to use: *cut-off plus credit* in EPDs of construction products, *simple cut-off* in EPDs of other products, and *CFF* in PEFs.

When a standardized format is developed, a method for modeling recycling should be stipulated. In this context it is important to note that the LCA results from different producers must be comparable, and that the LCAs should also provide environmental information that is important to the audience. This might require that the study accounts for consequences of recycled content as well as post-consumer recycling. See the discussion on intra-policy LCAs above for more details on these criteria.

Comparative assertions should be credible and relevant to the audience, which can include policymakers or other actors. No general and objective recommendation can be made regarding what specific methods to use in the LCA. The choice of method can be made either based on a specified LCA standard or guideline and/or in dialogue with policymakers and stakeholders. Adhering to ISO 14044 requires that different applicable methods are used at least in a sensitivity analysis. It also requires that interested parties be included in a critical review to ensure that the allocation procedure makes the different products comparable.

Information about the life cycle can be relevant to, for example, other actors along the value chain as part of life cycle management or as input to their LCAs. Again, there is no objective ground to recommend a specific method. Instead, the method should ideally be chosen in dialogue with the intended audience. The results should at least be presented in a transparent and disaggregated manner to allow for the audience to interpret the study, to assess its relevance, and to modify the LCA if another approach is better suited for their application. Disaggregated presentation of results is particularly important if the modeling of recycling includes avoided processes (cf. Module D when the *cut-off plus credit* method is applied).

The *CFF* has several advantages in an LCA intended for external communication. It is well established through the broad consensus process during the development of the PEF guidelines. It accounts for the fact that market conditions vary between materials. It does this in an operational and relatively robust manner thanks to the default values given by the PEF guidelines.

On the other hand, the default values are currently given for a limited number of materials only. The *CFF* can make the LCA difficult and/or expensive to carry out, if the product includes materials for which no default values are given. This might significantly reduce the use of LCA among producers of complex products. The *CFF* itself is also complex, which increases the risk that LCA practitioners misinterpret the formula, and the risk that errors in the LCA remain undetected by reviewers or other readers of the LCA report. The LCA results can to a large extent be governed by highly uncertain data on the waste management and the avoided virgin materials production, which affects the credibility of the LCA.

LCAs for internal use

An LCA intended for internal use can be carried out to learn about the life cycle and its environmental impacts. This knowledge can be valuable as preparation for external communication on the life cycle or specific aspects of it. The knowledge can also be valuable as part of the basis for decisions on improvements of products and processes. A parallel use of several methods can be useful to communicate internally that an LCA can generate different results and to assess the robustness of the conclusions from the study.

The method(s) used for external communication are beneficial for the company to apply also in LCAs for internal use. This will contribute to guiding the development of products and processes in a direction that the company can get credit for in their external communication.

However, an organization can also benefit from applying complementary methods in LCAs for internal use. In a company that uses EPDs with *simple cut-off* for external communication, LCAs for internal use can still benefit from more advanced methods that account for impacts on other life cycles. These impacts might be too uncertain to include in any external communication, but still relevant as information to internal decision-makers, at least when large investments and other strategic decisions are contemplated.

On the other hand, day-to-day decisions in process optimization or product development benefit from LCAs that are generated rapidly and with low cost. This means that simple methods can be useful internally even when the external communication is a PEF or based on other complex LCAs. Ideally, the simple methods should be at least rough approximations of the more complex LCA. An LCA with a *simple cut-off* is typically a poor approximation of most complex LCAs, because it disregards potentially important aspects outside the product life cycle. A *50/50* method is a better, albeit still rough, approximation of the more complex *CFF* and *price-elasticity* methods.

Even though a poor approximation of complex methods in most full LCAs, the *simple cut-off* has several advantages in LCAs made for internal purposes in industry. It is a commonly used approach. Inhouse engineers are more likely to learn a simple method. The LCA excludes impacts on other life cycles, which contributes to emphasizing the processes of the company. When the use of recycled material in the product is low, the approximation that this material is environmentally free is acceptable and the *simple cut-off* method is sufficient for cradle-to-gate studies. In full LCAs, the *simple cut-off* is likely to be a worst-case approach for such products, because it does not give any credit for impacts avoided through material or energy recovery in waste management. As a worst-case approach it can be useful to manage risks.

Conclusions, utilization, and steps forward

From our assessment, pilot testing in case studies, and debate on methods for modeling recycling, we cannot conclude that one method is the best. Different methods are likely to be adequate depending on the application, because each type of application has its own requirements on the method (see Table 7):

1. If the purpose is to provide basis for policy-decisions or other strategic decisions, the LCA should generate as much relevant knowledge as possible. This can also be important for LCAs used by companies to inform their stakeholders about the environmental impact of their products and activities. In these applications (colored red in Table 7), it is useful to regard LCA as a learning process rather than a calculation tool. This suggests that the methods in the LCA should be tailor-made to make the learning process efficient and generate as much knowledge as possible in the specific case study.
2. If the LCA is made within the framework of environmental labelling, green procurement, or to make environmental assertions to authorities or customers (blue in Table 7), LCA is mainly a tool for calculating reproducible results. To make results from different studies comparable, the same method is used in all studies and this method must be robust and well-defined to ensure different studies are comparable.
3. For frequent use of LCA to support, for example, day-to-day decisions in product development (yellow in Table 7), it is important that the LCA can be carried through in a short time. The methods in the LCA must be predefined and easy to use. The ease of use can also be vital for other application areas, such as a widespread use of environmental declarations.

Table 7: The requirements on the method vary with the application. Red color indicates that the main requirement is to generate relevant knowledge. Blue indicates that the method must be robust and generate reproducible and comparable results. Yellow indicates that the main criterion is the ease of use.

Application area	LCA used as learning process with tailor-made method(s)	LCA used as a calculation tool with predefined method
Policymaking	Develop basis for policy-decision	Required by a policy instrument
External communication	General communication on product and its environmental performance	Environmental Product Declarations, etc.
Internal use	Develop basis for strategic decisions	Day-to-day decisions

Generating relevant knowledge

What information is relevant is at least in part subjective. If the audience and decision-makers are only interested in the environmental burdens of the product life cycle, the cut-off methods are well suited to generate the relevant knowledge. When the LCA is used for internal decision-making at a company, it can be an advantage that the cut-off approach excludes impacts on other life cycles, because this makes the processes of the company more visible (cf. the chapter *Debating the methods*).

If the actors are interested in what part of the global environmental burdens belong to the product, the LCA should be attributional and all methods that fit in an ALCA can be applicable. A sensitivity analysis with two or three different attributional approaches, as required by ISO 14044, can be effective to investigate and illustrate the sensitivity of the ALCA results to the modeling of recycling. To help decision-makers better understand the results, the LCA report should also explain what views the allocation methods reflect, for example:

- *Allocation to material losses*: material lost must be replaced by virgin material. Hence, the environmental benefits of recycling are attributed to products that are recycled after use. This means the method gives incentives to develop recyclable products and to recycle them after use.
- *Allocation to virgin material use*: material extraction from the Earth means waste disposal is inevitable. Hence the environmental burdens of virgin production and final disposal of the material are both attributed to the products where the virgin material is used. This approach typically gives a strong incentive to the use of recycled material.
- *50/50 methods*: supply of and demand for recyclable material are both required for recycling to occur. To reflect this fact, the environmental benefits of recycling are equally divided between products that are recycled after use and products that contain recycled material. This method typically gives incentives to the use of recycled material as well as to recycling of products after use.
- *Price-based allocation*: the more a recycled material loses in economic value, the sooner it will be disposed of and replaced by virgin material. Hence, virgin material production (and arguably also final disposal) of the material is allocated to a product in proportion to the value loss of the material.

If the decision-makers are interested in how the product or their decisions affect the environment, the LCA should be consequential and focus on modeling the foreseeable consequences of the product or the decision. Several methods potentially fit in a CLCA, but each has limitations, for example:

- The *CFF* does not account for the waste disposal avoided through recycling.
- The *price-based substitution* does not account for impacts on the balance between supply and demand on the market for recyclable material.
- The *price-elasticity methods* do not account for losses in material quality, which can affect future recycling of the material.

The most advanced consequential methods are complex and can be difficult to apply in practice. This holds particularly for the *price-elasticity methods*, because estimates of the own-price elasticity of demand and supply on the markets for recyclable materials are scarce. Sometimes, however, simpler methods can be applied as a proxy for the more advanced method. For example, a *50/50 method* can be used as a proxy for the *price-elasticity method* (Ekvall 2000).

Generating comparable results

A method is more reproducible and generates more comparable results if it leaves no or little room for the LCA practitioner to adjust its design or input data (cf. the chapter *Criteria for assessing allocation methods*). The design of the method is more fixed if the method is defined in clear detail. The *simple cut-off* method and the *CFF* have the advantage that they are part of the EPD and Product Environmental Footprint frameworks, respectively. These frameworks allow for such detailed description of the methods to be included in Product Category Rules (PCRs) or Product Environmental Footprint Category Rules (PEFCRs). The standards for EPDs of construction products are difficult to interpret (see *cut-off plus credit* in the chapter *Methods for modeling recycling*), but a PCR can make the interpretation easier also for this method.

The *simple cut-off* method also has the advantage that it does not require data beyond the product life cycle. This leaves less room for manipulating the LCA results through the choice of data sources.

Attributional versions of *allocation to material losses* or *virgin material use*, or the *50/50* method require input data for modeling virgin material use and/or final waste disposal that are part of other product life cycles. However, these approaches can be made relatively reproducible if a guideline stipulates how these processes should be modelled, for example using global average data.

The *CFF* and other consequential methods have a drawback in that they require input data on avoided processes in other product life cycles. The PEF guidance provides default data for Factor A and material quality, but not for assumptions and data sources for the avoided processes. The LCA results can be heavily influenced by these choices. This leaves plenty of room for subjective choices and even manipulation of the LCA results. Detailed guidance in, for example, PEFCRs can reduce this problem by stipulating what assumptions should be made regarding the avoided virgin material production.

Ease of use

All methods were tested in case studies made by practitioners with varying knowledge, skills and experience of LCA. The successful testing of the methods implies that all methods are relatively easy to apply. However, the case studies were made with support of an Excel calculation sheet with equations and default data. This meant the LCA practitioners did not have to face all challenges in interpreting the methods and collecting data. It became possible to test all methods in the case studies, but it also meant the test did not fully capture how comprehendible and feasible the methods are.

A method can be expected to be easier to understand and, hence, apply if it has a simple structure. The *simple cut-off* method has the simplest structure possible. The most complex of the twelve methods in this report are the *price-based substitution* and the *CFF*.

Our case studies demonstrate that a method is also easier to apply if the guideline or description of the method includes default data. Here, the *CFF* has an advantage. The *simple cut-off* is even easier in this respect, because no data beyond the boundary of the product life cycle are needed. The *price-elasticity methods* are probably the most challenging when it comes to data collection.

The method might be easier to understand if the LCA practitioner perceives it to be fair, relevant and/or legitimate. Our case studies demonstrate that a calculation tool can facilitate the application of all methods. All methods are also likely to be easier to understand and apply with increasing experience from using the method. This means ease of use is not only an inherent property of the method, but significantly affected by the context in which it is used.

Utilization of project results

Information and results from this project have been disseminated through many channels (see *Publication list* and *Project communication* below).

One of our objectives has been to contribute to the ongoing development of and debate on the PEF methodology and international standardization. At least three project partners – the Swedish Environmental Protection Agency, IVL and Essity – participated actively in the PEF process. The researchers responsible for the development of the PEF guidelines received drafts of our report. They will also get the final report. It is difficult to determine whether our contributions will have any impact. If nothing else, the project helped to increase the knowledge and (it seems) the acceptance of the project's partners for PEF guidelines.

Several project partners (IVL, Chalmers, KTH, Tetra Pak, Essity and Jernkontoret) are involved in the current work on the international standard on LCA, ISO 14044, where much focus is on a new annex describing how allocation problems should be handled in LCA. Modeling of material recycling is not explicitly covered by this annex, but strong links exist because open-loop recycling is also an allocation problem in LCA. Our contributions have had some impact in the new annex.

An important part of the utilization comes from the many participants in the project moving on in their working life with better understanding of how material recycling should and can be modeled in LCA and similar environmental assessments. These participants include representatives of two universities, two institutes and one consulting firm, nine industrial companies, one industry association, and two authorities. The improved understanding gives a better basis for methodological decisions in LCA as well as an improved ability to interpret LCA results. This can contribute to making LCAs a better basis for decisions in industry and authorities.

Steps ahead

We plan to continue contributing to the PEF and ISO processes after this project is completed. Several research questions also remain at the end of the project. For example, this report focusses on recycling of materials after use in products. To a large extent, the methods and discussions are likely to apply also to recycling of production waste from, for example, the manufacturing industry. Further analysis and discussion are required, however, to decide to what extent they apply, and to what extent modeling of recycling of production waste requires other methods or considerations than the modeling of recycling of post-consumer waste.

Several of the methods in this report can be described as attempts to model the consequences of recycling. This goes, for example, for the *CFF*, *price-based substitution*, and consequential versions of *allocation to material losses*, *50/50*, and *price-elasticity methods*. Further analysis is required to decide how recycling should ideally be modeled to reflect the foreseeable consequences of using recycled material and the foreseeable consequences of recycling a material after use.

With several of the methods, an LCA risks giving no incentive to recycle material after use even when recycling is good for the environment, i.e., when $E_V + E_D - E_R > 0$. The risk is greater when the alternative waste treatment brings net benefits for the environment ($E_D < 0$) through, for example, energy recovery. In such cases, LCAs with a simple *cut-off* or *economic cut-off* will give an incentive not to recycle the material. An LCA with most other methods might also give an incentive not to recycle the material. This is because the LCA will include only part of the benefit of recycling ($E_V + E_D - E_R$) but the full benefit of energy recovery (E_D). The *CFF* includes a Factor B, which allows for including only part of the benefit of energy recovery in the LCA. Factor B is rarely used in practice, however. Further analysis is required to decide when and how Factor B can be used. The conclusions from such an analysis would probably be applicable also in many LCAs that do not apply the *CFF*.

In our discussions on modeling of recycling, we distinguish between methods that are applicable in ALCA and CLCA. A similar distinction can be useful for methods to model energy recovery.

Publication list

Ekvall T, Brandao M. 2020. Modelling material recycling in life cycle assessment: how sensitive are results to the available methods? Chapter in forthcoming *Handbook of the Circular Economy*, based on the chapter *Methods for modeling recycling* in this report.

Project communication

During the project several communications efforts have been made to lift results and inform about the project process. Swedish Life Cycle Center has written four news articles for their website during the project and these articles have also been shared in the center's social media channels and newsletters to reach a wider audience. The project website, https://www.lifecyclecenter.se/projects/modeling-of-recycling/, has been used as a base for communication throughout the project. Information about the project has also been disseminated through the website and newsletter of IVL.

Interim results were presented at the Worldsteel Association's LCA expert meeting, at an international conference with both researchers, companies and authorities (Life Cycle Management 2019), at a Network Conference organized by Swedish Life Cycle Center, and internally at IVL. Several hundred representatives from business, research and authorities participated in Life Cycle Management 2019. The Swedish Life Cycle Center Network Conference gathered around 50 life-cycle professionals from both academia, industry and authorities. To disseminate the knowledge and to get feedback to the project, drafts of the report were also sent to interested external researchers. The description of the twelve methods is about to be published as a chapter in the *Handbook of the Circular Economy* (see above).

The final results are presented in this project report, which be published at RE:Source, IVL and Swedish Life Cycle Center. A press release will be distributed to inform media about the project and the finalized report. A webinar with more than 100 participants was hosted by Swedish Life Cycle Center to disseminate the results; a recording of this webinar is available on YouTube: https://youtu.be/0Q456-K-P8M .We also planned to present the final results at a second conference (Circular Materials Conference). This conference was unfortunately postponed because of Covid-19.

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Annex 1. Analysis and revision of criteria in Ekvall (2018)

Table 1.1. Criteria for good environmental assessment methods and proposed revised criteria for good recycling allocation methods. Second column is in Swedish, as Ekvall (2018) writes in Swedish. A version in English was recently published (Ekvall 2020).

Original criteria, translated from (Ekvall 2018)	Motivation and description of criteria	Critical analysis of criteria	Revised criteria for "good recycling allocation methods"
Main criterion: Contribute to reducing humans' overall negative environmental impact, or at least per produced functional unit (Bidra till att människans negativa miljöpåverkan minskar totalt eller åtminstone per enhet producerad nytta.)		A method as such does not have an impact but can create incentives for improved product life cycles. If interpreted in the context of recycling allocation, a good method should create incentives to take actions that lead to reduced overall negative environmental impact, or at least per functional unit. The main criterion is rephrased to mirror this. An alternative type of main criterion was considered but rejected. It entailed prescribing in the main criterion what end-of-life solutions are preferred from an environmental point of view, based on previous findings, rather than leaving it to the application of the allocation methods to identify those preferred solutions. In this case a good allocation method would be one that steers towards the preferred waste treatment methods. Several sub-criteria focusing on scope and quality of the assessment would then be superfluous. This approach would simplify the process of identifying good allocation methods and create incentives for reduced environmental impact in most, but not all cases, and was therefore rejected.	**Main criterion** A good method for allocation of recycling should create incentives for solutions that reduce overall negative environmental impact, or at least per produced functional unit, of product life cycles.
A. Easy to use (Lättanvänd)	"Hur ofta miljöbedömningar görs beror på hur … hur **lätta** metoderna är att använda och hur **dyra** studierna blir. Detta beror i sin tur på hur **komplexa** metoderna är och på i vilken utsträckning de **data och modeller som behövs finns tillgängliga**. Metoden blir mer **kostnadseffektiv** om de resultat den genererar dessutom kan användas i flera olika beslutssituationer. Då behöver data inte samlas in lika många	This criterion covers several different aspects of the ease of use, which are more easily assessed if expressed as separate criteria. They are therefore split in different criteria. **Easy to use** is introduced as a separate criterion covering only perceived level of theoretical complexity by the users of the allocation method as such. This is a subjective criterion, depending on the knowledge and experience of	**Easy to use** The allocation method is perceived by the users as being easy to use, in terms of having low level of theoretical complexity. **Readily available data** Data required to apply the allocation method is readily available from e.g. stakeholders or databases or given as default values as part of

Original criteria, translated from (Ekvall 2018)	Motivation and description of criteria	Critical analysis of criteria	Revised criteria for "good recycling allocation methods"
	gånger, och även beräkningsarbetet minskar. Det är alltså en fördel om metoden är **enkel** och **billig** att tillämpa, och om dess resultat är lätta att **generalisera** till andra situationer." (p. 10)	the user. Different level of complexity can be acceptable in different decision contexts. **Readily available data** is introduced as a separate criterion covering availability of data needed to apply an allocation model in a certain decision context. Even in situations where data is available, it may not be rapidly available or cheap enough for certain applications. **Generalizable results** is introduced as a separate criterion covering whether the method generates results that are valid under different circumstances. An example would be cut-off at End-of-life, which allows results to be generalized to situations with varying recycling practices, as these steps would be excluded. Another example would be prescribed assumptions for EoL modeling, as this leaves no freedom to adjust the model to case specific circumstances. Cost efficiency of a method follows as a result if it is easy to use, relies on easily available data, and generates generalizable results. Hence, it is not introduced as a separate criterion.	the description of the allocation method. **Generalizable results** Through its design, the allocation method generates results that apply equally well under different case specific conditions.
B. Accurate (Rättvisande)	"... informationen bör vara så **rättvisande** som möjligt, det vill säga så **fullständig, korrekt** och **exakt** som det går. Den bör också gå att lita på i den meningen att den **inte är osaklig eller för subjektiv eller osäker**. Det är alltså en fördel om metoden ger studien ett **helhetsperspektiv** och om den ger en så **verklighetsnära** och **noggrann** bild som möjligt av det som faktiskt ska studeras. "	This criterion covers several different aspects of accuracy, which are more easily assessed if expressed as separate criteria. They are therefore split in different criteria. Aiming at models to be as complete, correct, exact, and close to reality as possible may be neither feasible, nor necessary. Model simplification is always necessary. Allocation will always remain a methodological choice and there is no absolute correct way of modeling. Rather than focusing on the correctness or accuracy, focus can be on how "fit for purpose" an allocation method is.	**Reflects environmentally decisive system characteristics** The allocation method represents environmentally decisive processes and flows. **Life cycle scope** The allocation method should facilitate or at least allow for a life cycle approach to be maintained in the system model. **Explicit, justified, and evaluated** The allocation method is documented explicitly, justified, and evaluated (through

Original criteria, translated from (Ekvall 2018)	Motivation and description of criteria	Critical analysis of criteria	Revised criteria for "good recycling allocation methods"
		When focus is on a model's fitness for purpose, the "correctness" of an allocation model is captured in its ability to **reflect environmentally decisive system characteristics** with adequate level of detail. **Life cycle scope** is introduced as a new criterion, to make explicit what is meant by a systems perspective and to ensure that the allocation method is designed such that a life cycle approach is maintained in the system model. **Explicit, justified, and evaluated** is introduced as a new criterion to handle prejudiced/partial allocation (unreflectingly based on the norms or values of the modeler) and subjective allocation (based on an explicitly documented choice in situations where choices need to be made). This however still leaves freedom to the user to make choices leading to different results, which is a form of model uncertainty. More robust methods in terms of reduced model uncertainty is achieved if they are **Reproducible** (described as a revision of "Robust" below). Parameter uncertainty is not dependent on the allocation method and therefore not covered by any criterion.	sensitivity analysis or scenario analysis).
C. Comprehendible (Begriplig)	"Miljöbedömningarna ska inte bara ge information, utan kunskap och insikter hos beslutsfattarna. Det kräver för det första att informationen behöver vara tillgänglig för dem, och för det andra att den är **begriplig**. Studien bör vara **transparent**, och så **lätt som möjligt att tolka och ta till sig**. Tolkningen underlättas av om de **begrepp** som används är **tydliga och intuitivt enkla att förstå**. Den kan försvåras om studien är mycket omfattande eller begreppsmässigt komplex. Det är alltså bra om metoden har en **enkel struktur** och bygger på **tydliga begrepp**."	This criterion partly has overlaps with other criteria, so that part of this criterion should be excluded and instead be covered by those. A **Comprehendible method** is achieved by clear structure of documentation and easily understood terminology of the method. A comprehendible method adds to transparency. Another aspect of transparency is complete documentation of data, which may not lead to a comprehendible method and	**Comprehendible** The allocation method is documented with clear structure and terminology in a way that can be understood by the expected users.

Original criteria, translated from (Ekvall 2018)	Motivation and description of criteria	Critical analysis of criteria	Revised criteria for "good recycling allocation methods"
		should therefore be handled as a separate criterion. Transparency in this sense is covered by the new criterion **Explicit, justified, and evaluated.**	
D. Inspiring (Inspirerande)	"För att kunskapen ska leda till beslut som minskar miljöpåverkan bör den vara **övertygande** och upplevas som **relevant** och **legitim**. Övertygande bör den bli om slutsatserna är **trovärdiga, tydliga** och **säkra. Trovärdighet** kan bland annat fås genom **känslighetsanalyser**. **Tydliga och säkra** kan slutsatserna bli om metoden **inte för med sig för stora osäkerheter eller har stora inslag av subjektivitet**. Det är alltså bra om metoden är **robust** (se nedan). En studie kan upplevas som **relevant** om den fokuserar på sådant som beslutsfattarna har **chans att påverka** och/eller har en tydlig anknytning till. Den får **legitimitet** om den upplevs som **rättvis**, **opartisk** och/eller **välförankrad**. Både **relevans och legitimitet** stärks om vi **tar hänsyn till avnämarnas kunskapsbehov** när vi väljer metod. Detta innebär att metoderna behöver situationsanpassas, och att olika metoder kan vara lämpliga i olika studier."	This criterion covers several different aspects, which are more easily assessed if expressed as separate criteria. They are therefore split in different criteria. It also has overlaps with other criteria, so that part of this criterion should be excluded and instead be covered by those. A convincing method is explained partly as one that is certain, which overlaps with the criterion "Accurate" in Ekvall (2018). However, under that criterion it was suggested to shift focus from the correctness of the model to **Reasonable results**, which is introduced as a new criterion above. It is also closely related to credible results and hence covered by that criterion. Avoiding subjectivity and partiality is covered by the new criterion **"Explicit, justified, and evaluated"** introduced above. **Relevant** is introduced as a new criterion, meaning that a recycling allocation method is designed in a way that decision-makers can influence the parameters that determine the impacts calculated through allocation, and that it is adjusted to the specific knowledge needs of affected stakeholders. **Legitimate** is introduced as a new criterion, to capture the perception by users of a method as being fair and well-anchored. Customizing an allocation method to the situation is relevant to many criteria, which is expressed as the need to consider the specific decision context when	**Relevant to decision-makers** The allocation method is designed in such a way that decision-makers can influence the parameters that determine the impacts calculated through allocation, and that it is adjusted to the specific knowledge needs of affected stakeholders. **Legitimate** The allocation method is perceived by users as well-anchored and fair.

Original criteria, translated from (Ekvall 2018)	Motivation and description of criteria	Critical analysis of criteria	Revised criteria for "good recycling allocation methods"
		assessing fulfillment of a specific criterion.	
E. Robust	"Med robust menas här att en studie ger ungefär **samma resultat oberoende av vem som använder metoden**. Detta gör att metoden blir **svårare att missbruka** och resultaten **inte är alltför osäkra**. Med **missbruk** menas miljöbedömningar som görs för att **stoppa eller försena ett beslut med positiva konsekvenser för miljön**, eller för att **försvara ett beslut med dåliga konsekvenser**. Metoden blir mer robust om den **inte kräver att användaren gör antaganden om osäkra fakta som påverkar resultaten kraftigt**. Den blir också mer robust om den **kopplar tydligt till studiens frågeställning**, om det finns **detaljerade riktlinjer** för hur metoden ska tillämpas, och om det finns en etablerad god praxis för tillämpningen."	This criterion covers several different aspects. The essential part of the criterion is that the method generates **Reproducible results**. This is achieved through a well-defined prescriptive method, where methodological choices and data choices are not left to the user. Ekvall (2018) also indicates that the method should be adaptable to the research question of the study. This can make the study more relevant to the decision-maker, but relevance is covered by a separate criterion. An adaptable method includes more dimensions of freedom which, in fact, risks making the results less reproducible. For these reasons we exclude adaptability as a criterion here.	**Reproducible** The allocation method leaves no or little room for the user to adjust its design or data, so that the method gives reproducible results and does not lend itself to misuse.

Annex 2. Criteria identified through literature search

Table 2.1. Comments and critical analysis of criteria found in the literature search refer to the proposed criteria in Table 1.1.

Criteria for good method for allocation of recycling	Motivation and description of criteria	Comment and critical analysis of criteria	Criteria identified as relevant
(Allacker, Mathieux et al. 2014) "Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives."			
Aim: *"This paper aims at analysing how secondary materials production and end of life recovery processes are modelled in life cycle-based environmental assessment methods in order to discuss their suitability in product policy-support contexts, with a focus on Sustainable Consumption and Production (SCP) policies. The equations prescribed in three published, widely recognised standards are evaluated. In addition, more recent modeling approaches that have been adopted in the context of two EU product policy initiatives (the Product Environmental Footprint (PEF) and the Resource Efficiency Assessment of Products (REAPro)) are similarly analysed. All of the methods are scrutinised against eight criteria which we deem to be important in product policy-support contexts".*			
General criterion: "follow a life approach"	Not mentioned as a specific criterion but referred to throughout the article as a general criterion that all other criteria should adhere to.	This criterion overlaps **"Life cycle scope"**.	No criterion added
General criterion: physically realistic modeling	Not mentioned as a specific criterion but referred to throughout the article as a general criterion that all other criteria should adhere to. Not defined what physical realism means.	This criterion overlaps with the criterion **"Accurate"** in Ekvall (2018). Cf. Appendix 1 for reasoning about how this criterion was revised.	No criterion added
Comprehensiveness	*"Comprehensiveness refers here to including all relevant aspects of the life cycle of the considered product, including both upstream and downstream processes – which is essential to satisfying the general criteria of following a life cycle approach as well as achieving physically realistic outcomes. Specifically, on the input side this requires considering resource flows and emissions associated with the production of virgin material as well as any recycled content. On the output side, resource flows and emissions, as well as any potential credits for avoided production must be accommodated both for material recycling processes as well as energy recovery processes. Emissions related to EoL treatment processes in the current lifecycle of concern need also be accommodated."*	This criterion describes what should be included to ensure a comprehensive life cycle approach, which overlaps **"Life cycle scope"**. It can be used to assess fulfillment of **"Life cycle scope"**, but it is not an additional criterion.	<u>Fulfillment of "Life cycle scope"</u> - including upstream processes, resource flows and emissions associated with the production of virgin material as well as any recycled content - including downstream processes, resource flows and emissions, as well as any potential credits for avoided production must be accommodated both for material recycling processes as well as energy recovery processes. - emissions related to EoL treatment processes in the current lifecycle of concern need also be accommodated."

Accommodating open-loop and closed-loop product systems	*"Accommodating both open-loop and closed-loop product systems is necessary to satisfying the criteria of following a life cycle approach as well as achieving physically realistic outcomes."*	This criterion specifies what should be included to ensure a comprehensive life cycle approach, which overlaps with **"Life cycle scope"**. It can be used to assess fulfillment of **"Life cycle scope"**, but it is not an additional criterion.	Fulfillment of "Sufficiently close to reality" Accommodating both open-loop and closed-loop product systems
Distinguishing % virgin and % recycled content of inputs	*"Distinguishing the % virgin and % recycled content of inputs is similarly essential both to the life cycle approach and to providing for physical realism."*	This criterion specifies what should be included to ensure a physically realistic modeling, which is considered under "B. True" in Ekvall (2018). It does not necessarily ensure a life cycle approach, as claimed by the authors. It can be used to specify how to assess fulfillment of the proposed revised criterion **"Sufficiently close to reality"**, but it is not an additional criterion.	Fulfillment of "Sufficiently close to reality" Distinguish % virgin and % recycled content of inputs
Considering recyclability and energy recovery rates	*"The recyclability and energy recovery rates refer to the proportion of the material in the product that will be recycled in a subsequent system or used for energy recovery, respectively. Accounting for these elements is essential both to the life cycle approach and to physically realistic modelling."*	This criterion describes a further specification of what should be included to ensure a physically realistic modeling, which is considered under "B. True" in Ekvall (2018). It does not necessarily ensure a life cycle approach, as claimed by the authors. It can be used to specify how to assess fulfillment of the proposed revised criterion **"Sufficiently close to reality"**, but it is not an additional criterion.	Possible specification of "Sufficiently close to reality" Considering recyclability and energy recovery rates
Including material and energy credits	*"Ascribing material and/or energy credits recognises displacement/substitution effects associated with recycling and/or energy recovery processes at the overall system level. Accounting for these elements is necessary for ensuring physical realism."*	This criterion can be used to specify how to assess fulfillment of the proposed revised criterion **"Life cycle approach"**, but it is not an additional criterion.	Possible specification of "Life cycle approach" Including material and energy credits
Accounting for changes in inherent properties of materials and/or down-cycling	*"Recycling processes often produce materials that are different from the original material (i.e. with different physical properties). Any such changes may determine subsequent uses of the materials, the products that may be displaced, the energy that maybe recovered, as well as the conditions of final disposal. For this reason, it is necessary to accurately reflect these changes when modeling EoL processes in order to maintain physically realistic modeling outcomes."*	This criterion describes a further specification of what should be included to ensure a physically realistic modeling, which is considered under "B. True" in Ekvall (2018). It can be used to specify how to assess fulfillment of the proposed revised criterion **"Sufficiently close to reality"**, but it is not an additional criterion.	Possible specification of "Sufficiently close to reality" Accounting for changes in inherent properties of materials and/or down-cycling

Physical correctness of flows at individual product level or at overall (product cascade) system level	*"The correct modeling of physical flows at both the individual product and overall (product cascade) system level are important issues. A product level considers all processes related to the life cycle of that specific product, while a system level considers several products which are interrelated through EoL processes (e.g. recycling). Unavoidably, one is required to prioritise between the two levels. Physical correctness of flows at the product level, for example, inherently results in double counting at the system level and thus leads to physical incorrectness at the overall system level. This can be illustrated by a product consisting of 100% recycled content that is 100% recycled at EoL. To calculate the flows in a physically correct manner, the recycling process should be considered at the start of the product's life cycle and a second recycling process should be considered at its EoL. This results in two recycling processes in total at the individual product level. However, at the overall system level this leads to double counting, as the recycling process at the start of the product's lifecycle was also considered at the EoL of the previous product, and similarly the recycling process at the product's EoL will also be considered at the start of the life cycle of the subsequent product."* *"…several approaches are possible to avoid double counting at the overall (product cascade) system level, such as accounting only for the recycled content (100:0 approach) or accounting only for recycling at EoL (0:100approach) or by distributing the impacts of the recycling process over the previous and subsequent product (50:50 approach). In consequence, these approaches do not guarantee physically correct modeling at the product level (e.g. for products with recycled content being recycled at their EoL)."*	Both alternatives are possible and can be meaningful when creating recycling allocation models, depending on the decision context. In this project **"Life cycle scope"** has been determined as one criterion, including avoidance of double counting of processes when assessing fulfillment of this criterion. Therefore no criterion is added for this aspect.	No criterion added
Enabling consistency for a wide range of applications	*"Achieving reproducibility/consistency rather than providing flexibility and choices to the analyst is deemed essential for lifecycle-based methods to be used in a consistent way in product policy-support contexts. The method must be applicable to all products potentially considered within the context of either voluntary or mandatory applications. It must also ensure that the results of product system studies are generated in a comparable manner, and hence provide comparable results. This is, for example, necessary for the purpose of gauging performance relative to benchmarks, or meeting specific labelling requirements." "To enable*	This criterion overlaps **"Reproducible"**.	No criterion added

	consistency for a wide range of applications, the method should offer a "One-Equation-Fits-All"."		
(Allacker, Mathieux et al. 2017) "The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative." International Journal of Life Cycle Assessment 22(9): 1441-1458.			
Aim: *"This paper explains in detail the rationale behind the choice of the end-of-life allocation approach in the European Commission Product Environmental Footprint (PEF) and Organisational Environmental Footprint (OEF) methods. The end-of-life allocation formula in the PEF/OEF methods aims at enabling the assessment of all end-of-life scenarios possible, including recycling, reuse, incineration (with heat recovery) and disposal for both open- and closed-loop systems in a consistent and reproducible way. It presents how the formula builds on existing standards and how and why it deviates from them."*			
Physical realism	*"This criterion evaluates if the modelling correctly represents the flows and related mass balances. The analysis is made at product level and overall system level." "...if the mass balance is maintained in the product system, but also if the processes that take place are indeed accounted for."*	Specifies fulfillment of criterion identified from Allacker at al (2014): **Physical realism of flows.**	Fulfillment of "Physical realism" Modeling correctly represents the flows and related mass balances, at either product level or overall system level. Mass balance is maintained. Processes that take place are indeed accounted for.
Fair distribution of burdens and benefits in a product cascade system	*"...a "fair" distribution of burdens and benefits over the different products in the cascade system. The term "fair" is debatable and depends on the perspective of the individual. The assessment of this criterion in the paper reflects how the different formulas fit different viewpoints on "fairness". This criterion is hence analysed from different viewpoints and is not an excluding criterion, only an informative one."*	This criterion is related to **"Legitimate"**, explicitly concerning the views on distribution of burdens. It can be used as a possible specification of this criterion.	Fulfillment of "Legitimate" **Fair distribution of burdens and benefits in a product cascade system, with regard to** - virgin production impact distribution over cascaded life cycles - recycling process impact distribution over cascaded life cycles - disposal impact distribution over cascaded life cycles "Fair" can be determined according to decision context, consensus among stakeholders, or other
Practicality	*"...applicability to the majority of the products on the market. This criterion evaluates the feasibility of the chosen allocation approach and relates to the objective of being applicable for any product on the market." "...need to be applicable for all products on the market and need to be reasonably straightforward to apply" "...does not require the input of unknown*	This criterion overlaps with two proposed revised criteria "**Easy to use"** and **"Readily available data"**.	No criterion added

	parameters…the recycling process…the avoided virgin production…number of times a product/material is being recycled…"		
(Atherton 2007) "Declaration by the Metals Industry on Recycling Principles"			
Aim: The article is a declaration by the metals industry, signed by 17 metals branch organisations, comparing the recycled content approach and end-of-life recycling to assess how they guide decision-makers wishing to better manage metals and metal containing products.			
Should not create market distortions and environmental inefficiencies	*"If a designer specifies high recycled content in a well-meaning effort to reduce environmental impacts, it may stimulate the market to direct recycled feedstock towards designated products and away from production where recycling is most economical. For metals, where there is a limited supply of recycled feedstocks, market stimulation is ineffective and may result in inefficient processing and unnecessary transportation."*	This criterion focuses on avoiding economical market distortion and environmental efficiency (environmental gain per spent amount of money). This is not compatible with the main criterion, according to which reduced negative environmental impact is the overall aim.	No criterion added
(Boguski, Hunt et al. 1994) "General mathematical models for LCI recycling"			
Aim: *"This paper presents an allocated approach to recycling of postconsumer products."*			
Address the interdependency of the recycled and virgin product	*"…interdependency is important if a recycling system is to be supported by both the virgin product manufacturer and the recycler"*	This criterion is essentially covered by **"Life cycle scope"** and **"Physical realism of flows"**	No criterion added
Logical	It is not further explained what the authors mean by this criterion, but it is motivated by the statement that *"…allocation…will always remain an arbitrary decision because there is no scientific basis…"*	If this criterion can be interpreted as being close to reality and making sense in general, it is essentially covered by **"Reasonable results"** and **"Legitimate"**	No criterion added
Produce reasonable and understandable results	It is not further explained what the authors mean by this criterion, but it is motivated by the statement that *"…allocation…will always remain an arbitrary decision because there is no scientific basis…"*	This criterion is essentially covered by **"Reasonable results"** and **"Comprehendible results"**	No criterion added
Find general consensus among scientific practitioners	It is not further explained what the authors mean by this criterion, but it is motivated by the statement that *"…allocation…will always remain an arbitrary decision because there is no scientific basis…"*	This criterion is essentially covered by **"Legitimate"**	No criterion added
(Dubreuil, Young et al. 2010) "Metals recycling maps and allocation procedures in life cycle assessment"			
Aim: *"The aim of this work is to present guidance on the application of ISO 14044 to allocation procedures for metal recycling. As such, graphical patterns of metal recycling and generic "rules" for metal recycling maps are presented. The results are intended to be useful in assessing and validating the suitability of allocation procedures for metal recycling in the context of life cycle assessment (LCA) and assist in the understanding of metals flow patterns in product systems."*			
Based on sound empirical data	Parameters necessary to model metal recycling should be derived from metal maps, a "survey of generic metal flows".	This criterion overlaps with the criterion **"Accurate"** in Ekvall (2018). Cf. Appendix 1 for reasoning about how this criterion was revised.	No criterion added
(Ekvall 2000) "A market-based approach to allocation at open-loop recycling"			

<table>
<tr><td colspan="4">Aim: "This paper presents a model that takes the market aspects into consideration. It can be used in a life cycle assessment (LCA) to model the indirect effects either through system expansion or as a basis for allocation."</td></tr>
<tr><td>Simplify without losing too much relevant information</td><td>"Since most activities in the global technological system are interrelated, an action may have indirect effects that propagate through the whole global technological system. This system is too complex to analyse on the level of detail used in an LCA. Hence, it is necessary to simplify the system"</td><td>This criterion overlaps with the criterion "Accurate" in Ekvall (2018). Cf. Appendix 1 for reasoning about how this criterion was revised.</td><td>No criterion added</td></tr>
<tr><td colspan="4">(Ekvall and Finnveden 2001) "Allocation in ISO 14041—a critical review"</td></tr>
<tr><td colspan="4">Aim: "The adequacy and feasibility of methods recommended for allocation by the current international standard on life cycle inventory analysis (LCI) are reviewed. The review is based on the view that an LCI should provide information on the environmental consequences of manipulating technological systems."</td></tr>
<tr><td>Not be too time-consuming</td><td>Not further explained or motivated</td><td>This criterion is essentially covered by "Easy to use"</td><td>No criterion added</td></tr>
<tr><td>Result in accurate information about the environmental consequences of our actions</td><td>Not further explained or motivated</td><td>This criterion is essentially covered by the Main criterion</td><td>No criterion added</td></tr>
<tr><td>Result in comprehensive information about the environmental consequences of our actions</td><td>Not further explained or motivated</td><td>This criterion overlaps with the criterion "Accurate" in Ekvall (2018). Cf. Appendix 1 for reasoning about how this criterion was revised.</td><td>No criterion added</td></tr>
<tr><td colspan="4">(Ekvall and Tillman 1997) "Open-Loop Recycling: Criteria for Allocation Procedures"</td></tr>
<tr><td colspan="4">Aim: "In this paper, we build upon the early SETAC criterion that the procedure should be consistent with the study goal. Our aim is to investigate how such a consistency can be obtained. We discuss what properties are important in the allocation procedure in order to obtain the consistency. We also discuss what allocation procedures have these properties. The aim is to indicate what type of allocation procedures are appropriate for different study goals."</td></tr>
<tr><td>Effect-oriented causality

OR

Cause-oriented causality</td><td>"Effect-oriented: the relationship between the investigated system and its effects."

"Cause-oriented: the relationship between the investigated system and its causes."

Ekvall and Tillman (1997) argue that "…to be an efficient support for a decision, LCA results should reflect the environmental consequences of that decision…. the allocation procedure should be based on effect-oriented causal relationships."</td><td>Effect-oriented causality corresponds to a consequential modeling approach, and cause-oriented causality corresponds to an attributional modeling approach.

Both alternatives are possible and can be meaningful when creating recycling allocation models, depending on the decision context. A decision needs to be made on what alternative to choose, before considering other criteria.

Added as criterion to select either approach.</td><td>Causality
Effect-oriented causality (consequential)

OR

Cause-oriented causality (attributional)</td></tr>
<tr><td>Acceptability</td><td>"The results of an LCA are only effective in a decision situation when the decision makers feel that the results are relevant. This requires the use of allocation procedures in the study</td><td>This criterion is essentially covered by "Legitimate"</td><td>No criterion added</td></tr>
</table>

	which are acceptable to the decision makers…"		
Applicability	*"…the allocation procedure must be feasible. LCA practitioners have an interest in the allocation procedure being readily applicable. The commissioning party of an LCA also has an interest in reducing the cost and time demands related to the LCA. This means it is an advantage if the amount of information needed for the allocation procedure is small and the necessary data are easy to collect and interpret."*	This criterion is covered by "**Easy to use**" and "**Readily available data**",	No criterion added
(EC 2013) "Product Environmental Footprint (PEF) Guide"			
Applicable for both open-loop and closed-loop recycling		Covered by **"Life cycle scope"**	No criterion added
If relevant/applicable, can accommodate re-use of the product being assessed.	*"This is modelled in the same manner as recycling."*	Covered by **"Life cycle scope"**	No criterion added
If relevant/applicable, can accommodate downcycling.		Covered by **"Life cycle scope"**	No criterion added
If relevant/applicable, can accommodate energy recovery.		Covered by **"Life cycle scope"**	No criterion added
(Frischknecht 2006) "Notions on the Design and Use of an Ideal Regional or Global LCA Database"			
Aim: *"This paper describes major requirements on the way towards an ideal national background LCA database in terms of co-operation, but also in terms of life cycle inventory analysis (LCI) and impact assessment (LCIA) methodology."*			
No criteria should be used. Models should represent the most approriate content with regard to what is preferred in each LCA	*"Aspects such as LCI modelling or allocation involve value judgements and subjectivity and it is doubted whether it is useful to try to reach consensus at all (or even enforce one particular approach)." "To allow for a plurality of approaches and to try to support such a plurality with transparent and open LCI databases is strongly preferred."*	Whether to use criteria or not when selecting allocation method is a subjective choice. Both alternatives are possible and can be meaningful when creating recycling allocation models, depending on the decision context. A decision needs to be made on what alternative to choose, before considering other criteria. Added as criterion to select either approach.	**Use of criteria** No, allow plurality (no criteria) OR Yes, apply criteria
(Frischknecht 2010) "LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency"			
Aim: *"This paper describes major requirements on the way towards an ideal national background LCA database in terms of co-operation, but also in terms of life cycle inventory analysis (LCI) and impact assessment (LCIA) methodology."*			
Strong sustainability modeling approach vs Weak sustainability modeling approach	Strong sustainability modeling approach means that human capital and natural capital are complementary but not interchangeable. Weak sustainability modeling approach means that human capital can substitute natural capital	Both alternatives are possible and can be meaningful when creating recycling allocation models, depending on the decision context. A decision needs to be made on what alternative to choose, before considering other criteria.	**Sustainability model** Strong sustainability modeling approach OR Weak sustainability modeling approach

	"The recycled content (or cutoff) approach accounts for the environmental impacts at the time they occur. If a product is made of primary metal, the environmental impacts of primary metal production are attributed to this product. No credits are given in case the metal in the product might be recycled in the future (when its service life ended). This modelling approach is very much in line with the strong sustainability concept where natural capital (climate change credits) is not replaceable by man-made capital (concentrated aluminium)." *"The concentrated metal in the product, which is potentially recycled in the future (after its service life ended), is considered equivalent to the natural capital represented by a credit of avoided environmental burdens such as avoided climate change impacts. Thus, the end of life recycling approach is representing the weak sustainability concept"*	Added as criterion to select either approach.	
Risk-averse attitude vs Risk-tolerant attitude	*"The end of life recycling approach grants credits to metal recycling that may occur in ten, 20 or more years from now (in the case of metals used in buildings, this can easily be 40 years and more). This approach assumes that the metal will still be in demand by that time in the future. However, this is an assumption and cannot be taken for granted as the future cannot be known. This means that an environmental loan is borrowed from future generations. The risk of not being able or not being ready to pay back the environmental credit in the future is taken deliberately. Thus, the approach may be classified as risk-tolerant or risk-seeking."* *"The recycled content approach promptly accounts for those environmental impacts that are caused by the consumption of primary metal feedstock, disregarding the fact whether or not the product may be recycled in the future. The time frame within which recycling is likely to happen is considered too long to be able to make sufficiently reliable forecasts. The risk of accepting an environmental credit from future generations is not taken, representing a risk-averse mindset."*	Both alternatives are possible and can be meaningful when creating recycling allocation models, depending on the decision context. A decision needs to be made on what alternative to choose, before considering other criteria. Added as criterion to select either approach.	**Risk attitude** Risk-averse attitude OR Risk-seeking attitude
(ISO 2006) "Environmental management -- Life cycle assessment -- Requirements and guidelines"			
The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained	Not motivated	This criterion is covered by "**Explicit, motivated, and evaluated**"	No criterion added

The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.	Not motivated	This criterion is covered by **"Life cycle scope"**	No criterion added
Result in consistent information about the environmental consequences of our actions	Not motivated	This criterion is covered by **"Reasonable results"**	No criterion added
(Koffler and Finkbeiner 2018) "Are we still keeping it "real"? Proposing a revised paradigm for recycling credits in attributional life cycle assessment"			
Aim: *"…we propose a revised paradigm based on embodied burdens that is able to alleviate many ofthe most pressing issues associated with material recycling in attributional life cycle assessment."*			
Attributional vs Consequential		This criterion is covered by **"Causality"**	No criterion added
Conformant with ISO requirements		Conforming to ISO requirements does not in itself support the main criterion.	No criterion added
Avoid expanding the system boundary	*"…open to discussion which inventory should be subtracted…" "…even when the inventory has been identified, the question about the appropriate substitution rate remains anything but trivial…" "…substitution approach can lead to net negative life cycle burdens…hard to explain but easily misinterpreted…" "…will add an inventory to the product system that would otherwise have been considered external to the product system under study…"*	The authors argue that system expansion should be avoided because of uncertainty of what is to be avoided and because it can lead to non-intuitive negative burdens. Whether this is reasonable is however considered under the criteria of **"Physical realism"**, **"Life cycle scope"** and **"Legitimate"**	No criterion added
Not require any assumptions about substitution rates, neither implicit nor explicit		This criterion overlaps with two proposed revised criteria "**Easy to use**" and **"Readily available data"**.	No criterion added
(Klöpffer 1996) "Allocation Rule for Open-Loop in Life Cycle Assessment - A Review"			
Aim: *"In this review, the different allocation rules proposed are presented and discussed with respect to the criteria of mathematical neatness, feasibility and justice/incentive for both producers and users of secondary raw materials."*			
"Mathematical neatness, internal logic, no double counting."		Mathematical neatness and internal logic overlap with **"Comprehendible".** Avoiding double counting is covered by **"Life cycle scope" and "Physical realism"**	No criterion added
"Feasibility at a low level of information with regard to the actual use or origin of the secondary raw materials."		Overlaps with **"Readily available data"**	No criterion added
"Justice and incentive for producers and users of secondary raw materials."		Justice overlaps with **"Legitimate".** Incentive overlaps with **"Relevant".**	No criterion added

(Pelletier, Ardente et al. 2015) "Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible?"			
Aim: *"…we identify and compare the rationales for (and limitations of) different common approaches to solving multifunctionality problems in LCA."*			
"can be defended based on a clear rationale (for example, with reference to a specific form of causality)"	*"In the absence of such a principled and systematic basis, LCA guidelines and studies of similar systems undertaken by different researchers according to their own approaches/beliefs for solving multi-functionality problems are likely to produce divergent results. This may undermine the acceptance of LCA and its decision support potential"*	Covered by **"Explicit, justified, and evaluated"**	No criterion added
"results in an internally consistent, logically structured, and maximally representative model of the product system and associated environmental burdens."	*"In the absence of such a principled and systematic basis, LCA guidelines and studies of similar systems undertaken by different researchers according to their own approaches/beliefs for solving multi-functionality problems are likely to produce divergent results. This may undermine the acceptance of LCA and its decision support potential"*	Internally consistent and logically structured overlaps with **"Comprehendible".** Maximally representative overlaps with **"Physical realism"**	No criterion added
"the choice is consistent with the aims and intended applications of the analysis."	*"In the absence of such a principled and systematic basis, LCA guidelines and studies of similar systems undertaken by different researchers according to their own approaches/beliefs for solving multi-functionality problems are likely to produce divergent results. This may undermine the acceptance of LCA and its decision support potential"*	Overlaps with **"Apply no criterion"**	No criterion added
"comparable study results are produced across similar studies."	dito	Overlaps with **"Reproducible"**	No criterion added
(Saade, da Silva et al. 2015) "Appropriateness of environmental impact distribution methods to model blast furnace slag recycling in cement making"			
Aim: *"This paper analyses the appropriateness of available multifunctional modeling methods to distribute environmental loads between pig iron and bfs produced in the steelmaking process, and the influence that modeling choices have on LCA results for different blended cement types commercialized in Brazil."*			
"complete and conceptually consistent description"		Overlaps with **"Life cycle scope"** and **"Physical realism"**	No criterion added
"allows for consideration of potential improvements at whole-system level"		Overlaps with **"Life cycle scope"**	No criterion added
(Schrijvers 2016a) "Developing a systematic framework for consistent allocation in LCA"			
Aim: *"This paper reviews allocation procedures for recycling situations, with the aim to identify a systematic approach to apply allocation."*			
Consistent ("coherent, following logical reasoning")		Overlaps with **"Reasonable results"** and **"Physical realism"**	No criterion added

apply "a strict separation between the two modeling methods [attributional and consequential]"		Overlaps with "**Causality**"	No criterion added
(Schrijvers et al. 2016b) "Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA"			
Aim: *"…we identify five review criteria that indicate the degree of consistency in the proposed allocation procedure of official guidelines."*			
"Consistency between reuse, recycling, energy recovery and co-production."	*"single approach applied to all multifunctionality problems"*	This is a criterion that can be set at the system level. Consistency in choice of allocation principle is not necessarily desirable.. A decision needs to be made on whether to require consistency or not at the system level. Added as criterion to select either approach.	**Consistency in allocation principle at system level** Required OR Not required
"Consistency between the LCA goal and the proposed method."	*"for different LCA goals different allocation procedures could be appropriate"*	Overlaps with **"Apply no criterion"**	No criterion added
"Consistent application of the attributional and consequential approaches."	*"average market data used in attributional LCA and marginal data in consequential LCA"*	Overlaps with "**Causality**"	No criterion added
"Consideration of the market situation of the material."	*"market-situation of the material taken into account in the choice of substitution method"*	Overlaps with "**Reasonable results"**	No criterion added
"Consistent approach for open-loop recycling with and without loss of inherent properties."		Overlaps with **"Life cycle approach"**	No criterion added
(Stamp, Althaus et al. 2013) "Limitations of applying life cycle assessment to complex co-product systems: The case of an integrated precious metals smelter-refinery"			
Aim: *"This study examines methodological requirements for assessing complex co-product systems using attributional LCA through a static, gate-to-gate inventory model that quantifies the environmental impacts of each of the metal products of an integrated precious metals smelter-refinery."*			
"capture the complexity of the system"	*"The complexity of a smelter-refinery cannot be captured by static, attributional inventory models, which is why the choice of allocation rationale remains arbitrary. Instead, marginal, parameterized models are needed; however, such models are substantially more time and data intensive and require disclosure of more detailed, process specific data."*	Overlaps with **"Reasonable results"**	No criterion added
"reflect the business model or other system drivers"	Not motivated	Overlaps with **"Reasonable results"**	No criterion added
(Tillman 2000) "Significance of decision-making for LCA methodology"			
Aim: *"Decision-making is central to life cycle assessment (LCA), both in the sense that LCA may be used as decision support and in the sense that different methodological choices in LCA are relevant to different applications. This latter issue is pursued in*			

this paper: i.e., how the decision-making context, and thus goal definition, may be used to guide methodological choices in LCA."			
Cause-oriented causalities Vs Effect-oriented causalities	*Cause-oriented causalities describe the relationships between the investigated system and its causes; effect-oriented causalities are the relationships between the investigated system and its effects. Economic profit from a system is one of the reasons a system exists, and it has been proposed that gross sales value be used as a basis for allocation [8]. This reflects an accounting, or retrospective, perspective. System enlargement is done to describe the full effects of a change, and is thus an example of an allocation procedure based on effect-oriented causality"*	Overlaps with "**Causality"**	No criterion added
(Weidema and Schmidt) "Avoiding Allocation in Life Cycle Assessment Revisited"			
Aim: *"We therefore revisit the issue [the problem of coproduct allocation], stressing a key argument for system expansion that has not yet been adequately described in the scientific literature—namely, that allocated systems nearly always fail to maintain mass and energy (and carbon) balances, whereas system expansion by its nature always ensures that mass and energy balances are maintained intact."*			
"maintain material balances"	"...key argument for system expansion that has not yet been adequately described in the scientific literature—namely, that allocated systems nearly always fail to maintain mass and energy (and carbon) balances, whereas system expansion by its nature always ensures that mass and energy balances are maintained intact"	Overlaps with "**Physical realism"**	No criterion added
(Werner, Althaus et al. 2007) "Post-consumer waste wood in attributive product LCA - Context specific evaluation of allocation procedures in a functionalistic conception of LCA"			
Aim:"*From this functionalistic conception of LCA [if the improvement options, which can be deduced from the LCI, are perceived by the decision-maker as to redirect the material flows at stake into more sustainable paths], this article develops a set of wood-specific requirements, an LCI of wood products has to fulfill to give adequate decision support under Central European conditions."*			
"...if the improvement options, which can be deduced from the LCI, are perceived by the decision-maker as to redirect the material flows at stake into more sustainable paths"		Overlaps with "**Relevant"**	No criterion added

Annex 3. Essity case study on plastic packaging

Pernilla Cederstrand, Essity

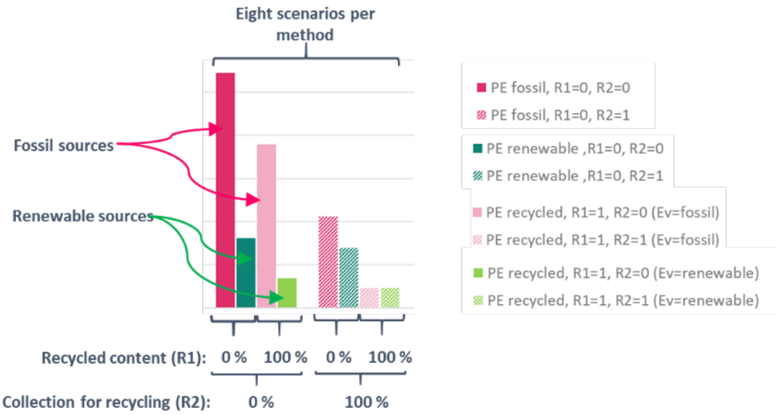

Figure 3.1: Schematic illustration of the eight scenarios included for different plastic packaging alternatives. 4 material content options, i.e. primary plastic (R_1 = 0) from fossil and renewable sources, recycled plastic (R_1 = 1), with primary production from fossil or renewable sources combined with 2 end of life options, i.e. 100 % incineration (R_2 = 0) or 100 % collection for recycling (R_2 = 1).

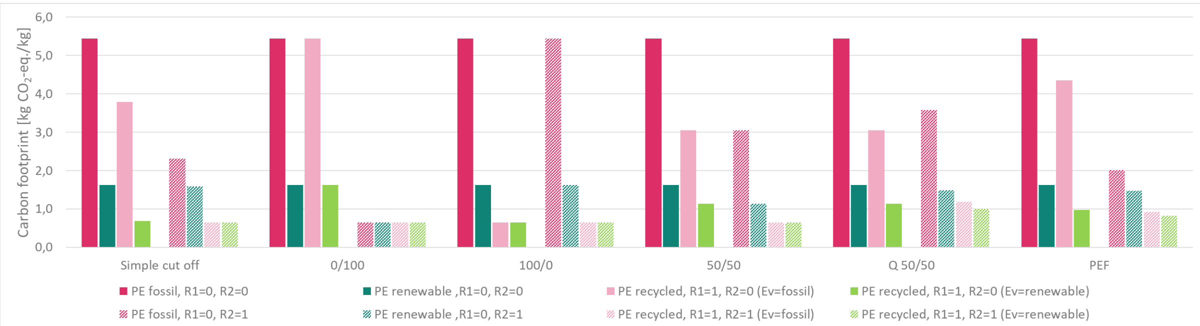

Figure 3.2: Carbon footprint results from the Essity case study on plastic packaging alternatives with application of selected approaches to allocation at recycling and with biogenic carbon removals attributed to final disposal.

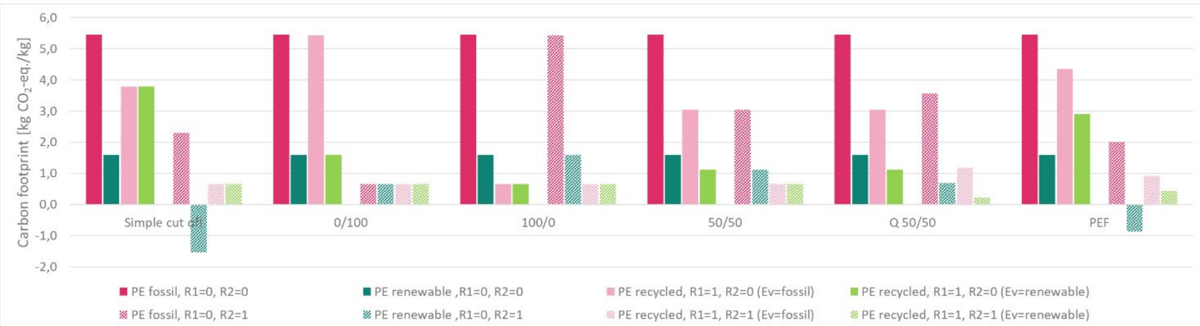

Figure 3.3: Carbon footprint results from the Essity case study on plastic packaging alternatives with application of selected approaches to allocation at recycling and with biogenic carbon removals attributed to primary production (cultivation).

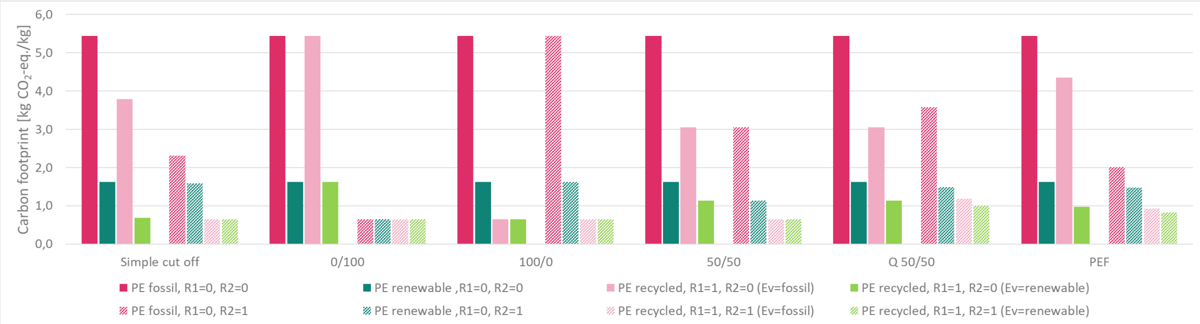

Figure 3.4: Carbon footprint results from the Essity case study on plastic packaging alternatives with application of selected approaches to allocation at recycling and with biogenic carbon removals attributed in accordance with EN 16485 and EN 15804.

Case study

The Essity case study focuses of assessments of different plastic packaging alternatives: produced from fossil or renewable raw materials that are virgin or recycled. After use, the packaging is either recycled or incinerated without energy recovery. When recycled after use, the material is assumed to replace material of the same origin: recycled plastics with fossil origin is assumed to replace similar, fossil-based plastics; recycled plastics based on renewable raw materials is assumed to replace similar, renewable plastics.

The case study was conducted by inhouse staff with long life cycle expertise and by using the calculation tool of the project. The reported data represents net carbon footprints (for simplification emissions and any removals are reported as a net) and where based on GWP 100. Generic data from the professional database related to the LCA software GaBi, where used for all life cycle stages used in the models. For data on quality, price, etc., the default data from the calculation tool was used i.e. those factors are not based on actual data.

The result interpretation focuses on the following allocation methods; Simple cut-off, Allocation to material losses (0/100), Allocation to virgin material use (100/0), 50/50 methods, Quality-adjusted 50/50 methods and PEF. A was set to 0.5 in the PEF method.

The following 8 scenarios where included:

- 4 different scenarios for content in plastic:
    - 100 % primary plastic from fossil sources
    - 100 % primary plastic from renewable sources
    - 100 % recycled plastic from fossil feedstock
    - 100 % recycled plastic from renewable sources
- Combined with 2 different scenarios for fate at end-of-life:
    - 100 % incineration without energy recovery

- 100 % collection for recycling

In addition, three different approaches where tested for treatment of biogenic carbon flows in the calculations.

- Attribution of biogenic carbon removals to the primary production, i.e. (E_V & E^*_V)
- Attribution of biogenic carbon removals to the final disposal, i.e. (E_D & E^*_D)
- Attribution of biogenic carbon removals as described in EN 15805 (Sustainability of construction works) and EN 16485 (Round and sawn timber – EPD – PCR for wood and wood-based products for use in construction) where any removals follow the carbon content of the product, i.e. is passed on to the next life cycle when material is recycled.

Emissions of biogenic CO_2 are in all cases included in the life cycle stage where they occur, i.e. e.g. at assumed incineration in the final disposal.

Results

Figure 3.1 presents the scenarios included in the case study on plastic packaging materials and how to read the charts. Figures 3.2-4 presents results for all scenarios for the selected allocation methods and with one chart for each the three different approaches regarding handling of biogenic CO_2 removals end emissions.

All methods, except the 100/0 method, shows lower absolute results for collection to recycling compared to incineration without energy recovery.

The absolute net carbon footprint results for the renewable materials differs significantly depending on what allocation method that is used and for some methods the absolute results differ also depending on what approach that is used for attribution of biogenic removals.

This means that different conclusions regarding what is the preferred option and the relative difference between the options can be drawn depending on what method and approach that is used.

The Allocation to material losses (0/100) and the Allocation to virgin material use (100/0) stands out in the results. The 0/100 method makes no difference on type of raw material used (primary, recycled, fossil, renewable) when collected for recycling and makes no difference between primary and recycled content when no collection takes place and hence not drive replacement of fossil materials. The 100/0 method instead takes only the type of raw material into account and makes no difference between disposed and recycled material at end of life.

Use of the Simple cut off method, the 50/50 method, the Quality-adjusted 50/50 method and the CFF (with A = 0.5) differs slightly in absolute results but would for this case study lead to similar conclusions regarding preferred options. However, when the packaging is produced from recycled material and recycled after use, the Quality-adjusted 50/50 method and the CFF are the only methods that distinguish between recycled material from renewable sources and recycled material from fossil sources, with a slight preference for materials from renewable sources.

Attribution of biogenic removals to final disposal and attribution of biogenic carbon in accordance with 15804 and 16485 seem (with our interpretation) to give exactly the same results. However, for some of the allocation methods, attribution to primary (virgin) production gives very different results. The simple cut off-, the quality-adjusted 50/50- and the PEF method have different absolute results depending on approach used for attribution of biogenic carbon and the simple cut of- and the PEF method shows negative overall footprints, i.e. they indicate net carbon sinks, for use of renewable primary material (R_1 = 0) when collected for recycling (R_2 = 1).

The differences in absolute results depending on approach for attribution of biogenic carbon for the three mentioned allocation methods would potentially lead to different conclusions regarding preferred options. As an example, for the simple cut of method; when the biogenic removals are attributed to final disposal the method would give incentives for use of recycled materials from renewable sources (R1=1) over use of primary material from renewable sources while when biogenic removals are attributed to the primary (virgin) production the method would give incentives to the opposite.

The 0/100, 100/0 and the 50/50 method gives in this case study the exact same results and incentives independent of approach for attribution of biogenic carbon removals.

Observations

In order for any method to work It should promote fair comparison versus competing products and systems, we think this is important:

- Actual environmental improvements in the life cycle should be rewarded by a lower result.
- Reward use of recycled material and collection, when appropriate, i.e. when the recycling process (including collection) has lower impact than the virgin process and the impacts from waste handling is greater than zero.
- Reward use of renewable materials when appropriate, i.e. lower net carbon emissions than fossil counterparts.

Other observations:

- All methods intentionally or unintentionally include value choices.
- No method is “perfect” and good to use in all situations. All methods have advantages and disadvantages.
- Many methods are poorly described in the original references and are hence difficult to understand.

- The difficulties to interpret and use some of the methods may lead to different results for different practitioners.
- Definitions of individual parameters are insufficient.
- Using different methods might lead to:
  - Different results on product life cycle level
  - Different conclusions regarding possible choices in product development and on what life cycle stages that are hot spots
- For many of the suggested methods, for example PEF's Circular Footprint Formula, there is a need of agreement on values to use.
- Some methods seem to be more suitable for the internal decision-making as well as in external communication.
- A difference with the PEF method compared to most of the other selected methods is that a significant part of the net results depends on generic data (E^{*}_{V}, E_{Rout} & E^{*}_{D}) that needs to be agreed on to make results comparable and readily available to at all be able to use the method. The use of generic data also has the effect that data representing the actual life cycle under study, i.e. parts that can be directly steered, only constitutes a limited part of the footprint results which means that the magnitude and effect of any changes (positive or negative) is smaller compared to when other allocation methods are used.
- None of the method descriptions include detailed guidance on treatment of biogenic carbon for renewable materials. We also found the description in 15804 and 16485 partly difficult to understand and difficult to apply to the different allocation methods.
- With increased use of materials from renewable sources as one of the suggested ways forward for increased sustainability, it is very important that all allocation methods can handle inclusion of biogenic carbon in the calculation, that guidance on this is added and that the mechanisms of the methods stays robust when doing so.
- Among the tested approaches for treatment of biogenic carbon, we prefer the attribution to final disposal (i.e. similar as the approach in EN 15805 and EN 16485) over attribution to primary production. One reason for this is that the latter method has the effect that materials with recycled content from renewable sources (i.e. assuming to replace renewable sources) are considered having the same footprint as recycled fossil materials in products that are not recycled after use.

Annex 4. SSAB case study on hot-rolled steel

Jonas Larsson, SSAB, and Gustav Sandin, IVL Swedish Environmental Research Institute

Case study

This case study focuses on evaluating low-alloyed carbon steel over an entire product life cycle. The calculations are made for a hypothetical end-product using 1 000 kg of hot-rolled steel strip products from SSAB's iron ore-based production in Scandinavia.

The end-product is a product exclusively made of steel and with a passive function during the use-phase, i.e. it will not have any energy consumption or need for maintenance, etc. during the use-phase. Also, the manufacturing of the end-product itself is deemed to be negligible.

The absence of environmental impact for manufacturing and use of the end-product will highlight the impact of using different methods for modelling the recycling.

The scenario is also quite common, for example in the infrastructure and construction sector.

The calculations required for the results in Figure 4.1. have been made by IVL Swedish Environmental Research Institute using the Excel based calculation tool of the project.

The source of the data for the virgin steel production is the environmental product declaration (EPD) for SSAB's hot-rolled strip products, which has been developed within this project.

Steel is a material, which is reusable and can be endlessly recycled. However, there are also some losses and in this study a recycling rate of 95% has been assumed.

When recycling the steel at the product's end-of-life, a scrap-based steel production will be used, which will replace iron-ore based steel. Both the recycling and the value of avoiding virgin steel will be calculated using global average data.

When evaluating recycling allocation methodologies, models that requires calculation data on how the external scrap market responds to changes in supply or demand have not been evaluated, due to lack of information. However, the European Product Environmental Footprint (PEF) has, at least partly, been evaluated. This is possible since there is a standard value given for steel as it relates to the Circular Footprint Formula and its Factor A, reflecting the dynamics of the scrap market.

In cases where a quality factor is used to describe differences between products from virgin and recycled origin, a factor of 1:1 has been adopted. This means steel is considered to have the same quality regardless of the production route.

Finally, the study has been limited to calculate the climate impact in CO_2 eq. only.

Results

Figure 4.1. shows the climate impact of the end-product, depending on the selected method for handling allocation of recycling.

This highlights the challenges associated with quantifying the benefits of recycling in LCA. Different methods emphasize different aspect of the studied system and there is no correct method per se.

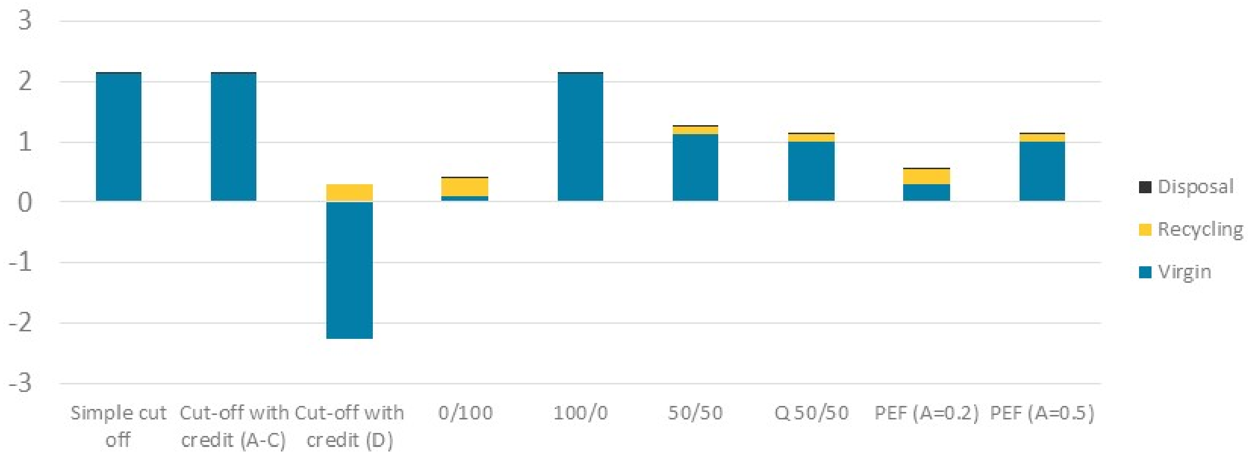

Figure 4.1: Climate impact in kg CO2 eq. per kg hot-rolled strip produced by SSAB, and its dependence on the selected method for allocating the impact of recycling. Manufacturing and use of the product in which the steel is used has been excluded.

Observations

Two main methodologies have been identified in this case study, both commonly used for recycling of materials, and also representing two extremes.

These two methods will be the main subject for the observations. These are the Simple cut-off method (also referred to as the recycled content approach), and the Allocation to material losses method (also referred to as the 0/100 and the avoided burden approach).

Simple cut-off

The method models scrap input as burden free, i.e., not bearing any environmental impact from the primary steel production. In this case, the original (iron ore based) production of the steel assumes the full environmental burden of these activities.

The simple cut-off method, therefore, promotes the increased use of recycled content in products.

A related method is the cut-off with credit, which is used, for example, in environmental product declarations (EPD) according to EN 15804. The net-result when subtracting the Module D value seems to be similar to the method of allocation to material losses.

However, in an EPD the credit is reported separately, and the net-result is not used in that way.

The method for allocation to virgin material use (100/0), as described in this project, has characteristics similar to the simple cut-off method.

Allocation to material losses

This method assigns an environmental value to steel scrap, i.e. an environmental burden is applied to already available scrap, and a credit is given when adding additional scrap from virgin production into the scrap market.

This method promotes the recycling of steel products when they reach the end of their useful life.

For most steel products and especially those produced from iron ore, applying the allocation to material losses approach results in an environmental “credit” from recycling the steel scrap produced during the manufacturing of the products and at its end-of-life, which can help offset the impacts from initial production.

This highlights the fact that a valuable resource (steel scrap) is generated by iron ore based production and can be used in place of raw materials during future production.

Methods in between the two extremes

In between the two extremes described earlier, there are several methods, which splits the environmental credit or burden between primary and secondary steel production:

- 50/50 methods
- Quality-adjusted 50/50 methods
- Circular Footprint Formula (part of the PEF methodology)

Let us consider the Circular Footprint Formula; Factor A is set between 0 and 1, to reflect the dynamics of the scrap market.

A = 1 will reflect a situation when no matter how much scrap enters the market, demand remains the same.

A = 0 will reflect a situation when no matter how much scrap enters the market, demand will adjust to take up the extra supply and recycle it.

When setting A = 0.5, credit is distributed evenly amongst adding additional scrap from virgin production into the scrap market, and the use of already available scrap, which results in a credit (or burden) equivalent to one half of the credit (or burden) calculated using the allocation to material losses method. This gives the same result as using the quality-adjusted 50/50 method.

When setting A = 0.2, which is the standard value given for steel, the use of already available scrap receives 20% of the recycling benefits, while the adding of additional scrap from virgin production into the market receives 80%. In this case the PEF result will be pushed close to the result when using the allocation to material losses.

Challenges related to data collection

In this study there are mainly three calculation factors that require special attention. These are described below.

The environmental impact (E_V) is supposed to reflect the impact of the specific production process, as if the input feedstock is 100% virgin material. However, as this process uses recycled material (which of obvious reasons is often the case when an allocation method has to be used), this requires some assumptions. In our case, we assumed the impact of the specific production process as it was based on almost 100% virgin inputs (97.4%). For other processes, using a larger share of recycled inputs, this may constitute a more significant problem.

The avoided environmental impact (E^*_V) is likewise supposed to reflect the impact of some generic, market-average production process, as if the feedstock is 100% virgin material. This suggests database data should be used, which leads to two questions. First, one need to know the share of virgin/recycled inputs to the process – this information is not always clearly given in LCI databases. Secondly, there may not always be data available reflecting 100% virgin input, if such production does not exist.

And finally, the environmental impact for the recycling process (E_{R2}). Finding data for E_{R2} is a similar challenge as finding data for E^*_V, at least in our case when the subsequent recycling is done outside the direct control of the company producing the studied product. For steel products, data of a generic recycling process (electric arc furnace, EAF) was not readily available as the existing database data on an EAF process did not reflect a process with 100% recycled inputs, i.e. it was a production processes that could only partly be labeled as a "recycling process".

To conclude, there were two main challenges in terms of data collection: to find data for "virtual" processes that does not really exist (using no or 100% recycled material input), to find data reflecting generic data, i.e. data of other processes that those over which the company performing the LCA (or providing LCI data) has control.

Conclusion and discussion

The selection of a recycling allocation methodology has a significant effect on the LCA results and can change the total environmental profile of steel products dramatically.

In this case study the climate impact for SSAB's hot-rolled strip products is 2.16 kg CO_2 eq. per kg steel product, when using the simple cut-off recycling allocation methodology, which is also the maximum value within this case study.

However, when applying the allocation to material losses approach, or the circular footprint formula (A = 0.2), the climate impact value is the lowest and only approximately 20-25% of the maximum value.

For SSAB in Scandinavia a transformation from the traditional blast furnace-based production route to the use of electric arc furnaces is under way. This will use scrap metal and also increasingly use fossil-free direct reduced iron.

If this case study would have been based on the future production set-up at SSAB, the outcome would most likely have been the opposite when applying the different recycling allocation methodologies.

Annex 5. Outokumpu case study on stainless steel

Camilla Kaplin, Outokumpu

Manufacturing of stainless steel-welded tubes was chosen as case study. The data represents one specific production route within the company. As this route has a relatively high scrap use ration (85%), a second case was built with the same input data but with the average scrap use ration of 50%.

Another case study was built around data that has been collected for the company EPD. In this case the exact end-use of the product (cold-rolled stainless steel) was not known. However, the assumption was that the steel would be used in a construction product, as this was the basis for the EPD. Data was collected from several production units and averaged into a product EPD for the whole company.

Results

Figures 5.1 and 5.2 show the climate impact of the end-product, depending on the selected method for handling allocation of recycling.

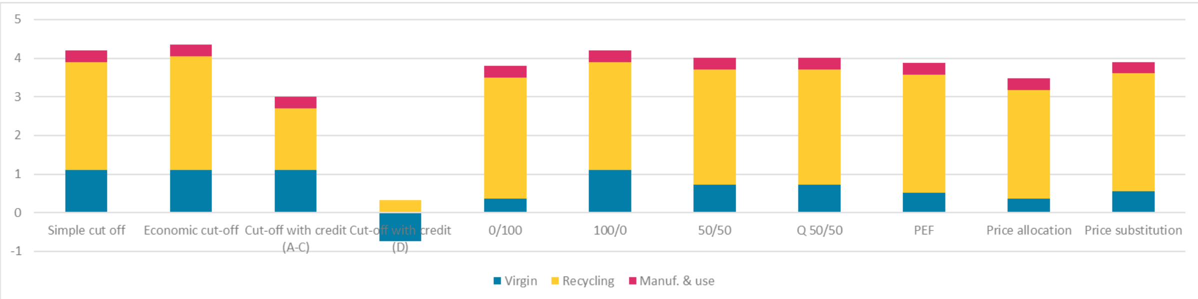

Figure 5.1: Climate impact in kg CO2 eq. per kg of stainless steel tube, with the scrap input ratio of 85%.

The results show that Cut-off with credit gives the lowest overall impact, even without including Module D. For the other methods in this evaluation there is not that much difference in the results.

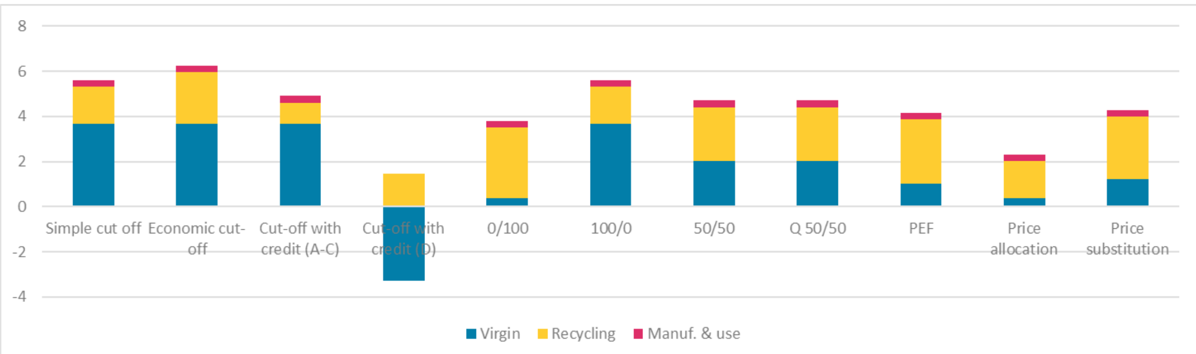

Figure 5.2: Climate impact in kg CO2 eq. per kg of stainless steel tube, with the scrap input ratio of 50%.

The lower scrap input ratio changes the outcome as Price allocation gives the lowest overall impact, followed by the 0/100 method. Now also the difference between 0/100 and 100/0 becomes more evident.

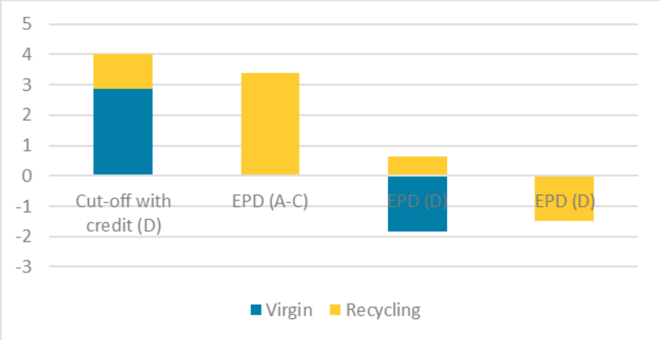

Figure 5.3: Climate impact in kg CO_2 eq. per kg of cold rolled stainless steel. EPD data and same data in the model investigated in this study.

Observations

For stainless steel the chosen scrap ratio has a significant impact. It affects the overall result, but there is also a change in which methods that give the lowest overall result depending on scrap ratio. With a lower recycled content, the difference between 0/100 and 100/0 methods become more apparent, while the two methods give quite similar results when recycled content was high.

Company EPD data was compared to the Cut-off with credit method since that should be what is applied in the EPD. Results were not identical although the same input data was used. There could be several reasons for this, either in the input data or in the formula. However, the time did not allow further investigation of this discrepancy.

Annex 6. Tetra Pak case study

Lars Winborg and Erika Kloow, Tetra Pak

Description of the product and data

The product in focus for this assessment is an aseptic beverage carton. Three different case studies have been included in order to assess the allocation methods.

The main material in the beverage carton is paperboard providing stability, strength and smoothness to the printing surface. Layers of polyethylene protect against outside moisture and enables the paperboard to stick to the aluminium foil. Aluminium foil protects against oxygen and light to maintain the nutritional value and flavours of the food in the package in ambient temperatures. The composition of the beverage carton assessed in this case study represents an average aseptic one litre package with cap (70% paperboard, 25% polyethylene and 5% aluminium foil). Average European data has been used for the raw material production for the beverage carton.

The packaging material is produced at Tetra Pak factories, where the paperboard is coated with polyethylene and aluminium foil, and then printed and cut. For the converting operations European average data from ACE is used.

Forming and filling of the beverage carton has been excluded from the assessment, and also transports to forming & filling, retail and consumer.

Collection of cartons for recycling is included in the study. The modelled recycling operation includes recycling of the fibres, the polymers and the aluminium. How beverage cartons are recycled varies between countries, and this case study models a fictive case based on average literature data.

For disposal, incineration without energy recovery has been modelled. This choice will generate the maximum potential impact of ‘disposal’

Data references are described in detail in Table 6.1.

Case studies

<u>Case 1</u> represents a beverage carton made of virgin materials, which is the current situation. It is assumed for the purpose of this study that the recycling rate is 100%.

‘Liquid Packaging Board’, ‘Aluminium foil’ and ‘LDPE’ as described in

have been used to model the GHG impact of the virgin material production. The ‘Paper recycling’ and ‘Plastic recycling’ are used to model the impact of the recycling process. ‘Virgin kraft’ and ‘LDPE’ are used to model the burden of the virgin material avoided through recycling (it has been assumed that the aluminium is included in the plastic stream).

Table 6.1: Detailed references of the data used in the case study.

Material/process	Reference
Liquid packaging board *(cradle-to-gate)*	ACE/ELCD. Based on “LCI dataset for Liquid Packaging Board (LPB) production” by IFEU October 2011.
Aluminium foil *(cradle-to-gate)*	“Environmental Profile Report, Life-Cycle inventory data for aluminium production and transformation processes in Europe”, February 2018, for the European Aluminium Industry Data for the year 2015
LDPE *(cradle-to-gate)*	“Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers, High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE)” PlasticsEurope, April 2014
Virgin kraft *(cradle-to-gate)*	Ecoinvent: RER corrugated board base paper, kraftliner, at plant *According to Ecoinvent report kraftliner is the most common fresh fibre corrugated board base paper.*
Converting beverage carton packaging material *(gate-to-gate)*	GaBi model based on process “Beverage carton converting” from ACE/ELCD Linked to EU-28 electricity, EU-28 Natural gas, EU-28 light fuel oil, EU-28 LPG
Injection moulding *(gate-to-gate)*	Ecoinvent: RER injection moulding
Collection for recycling *(gate-to-gate)*	“Material recycling versus energy recovery of used beverage cartons. Swedish perspective. For Tetra Pak”, IVL, 2013
Paper recycling *(gate-to-gate)*	Ecoinvent in GaBi: RER Corrugated board base paper, testliner, at plant. *According to Ecoinvent report testliner is the most common recycled fibre corrugated board base paper.*
Plastic recycling *(gate-to-gate)*	Internal GaBi model. Production of recycled polymers, average
Aluminium recycling *(gate-to-gate)*	Processing of foundry aluminium alloys ingot from scrap. “Environmental Profile Report, Life-Cycle inventory data for aluminium production and transformation processes in Europe”, February 2018, for the European Aluminium Industry Data for the year 2015
Paper incineration *(gate-to-grave)*	GaBi: EU-28, ELCD/CEWEP: Waste incineration of paper fraction in municipal solid waste (MSW). EPD with expired validity. *No credit for heat and electricity*
Aluminium incineration *(gate-to-grave)*	Ecoinvent: CH: Disposal, aluminium, 0 % water, to municipal incineration
Plastics incineration *(gate-to-grave)*	GaBi: EU-28, ELCD/CEWEP: Waste incineration of plastics (PE, PP, PS, PB) *No credit for heat and electricity*

Case 2 represents a beverage carton made of 100% recycled materials, which represents a **hypothetical** case. It is assumed for the purpose of this study that the recycling rate is 100%.

For production of recycled materials used in the beverage carton, the datasets 'Paper recycling', 'Aluminium recycling' and 'Polymer recycling' have been used. For recycling of the beverage carton, 'Paper recycling' and 'Polymer recycling' have been used (it has been assumed that the aluminium is included in the plastic stream). It has been assumed that the carton using 100% recycled materials requires a slightly heavier board than the virgin carton. The virgin materials used are the same as in Case 1. These virgin materials are also used to model the process that is avoided through recycling.

Case 3 represents a beverage carton made of 100% recycled materials, which represents a **hypothetical** case. It is assumed for the purpose of this study that the recycling rate is 0%.

For production of recycled materials used in the beverage carton, the datasets 'Paper recycling', 'Aluminium recycling' and 'Polymer recycling' have been use. It has been assumed that the carton using 100% recycled materials requires a slightly heavier board than the virgin carton. The virgin materials used are the same as in Case 1. These virgin materials are also used to model the process that is avoided through recycling. For disposal, incineration without energy recovery has been modelled based on the datasets 'Paper/Aluminium/Polymer incineration'.

Calculations

The Excel tool as provided by the project has been used for the modeling and generation of results. The calculations and reporting have been done by internal Tetra Pak staff.

Results

Figures 6.1-3 present results from the case study on beverage cartons.

The 0/100 (allocation to material losses) and the 100/0 (allocation to virgin material use) are the two extremes of the allocation methods. 0/100 allocates the full impact of virgin material extraction and disposal to the product system that disposes the product. The 100/0 method allocates the full impact of virgin material extraction and disposal to the product system that extract the virgin material. The PEF method allocates some virgin material use to systems using 100% recycled content.

The approaches that most clearly drive both recycling and recycled content are the 50/50 and the cut-off methods.

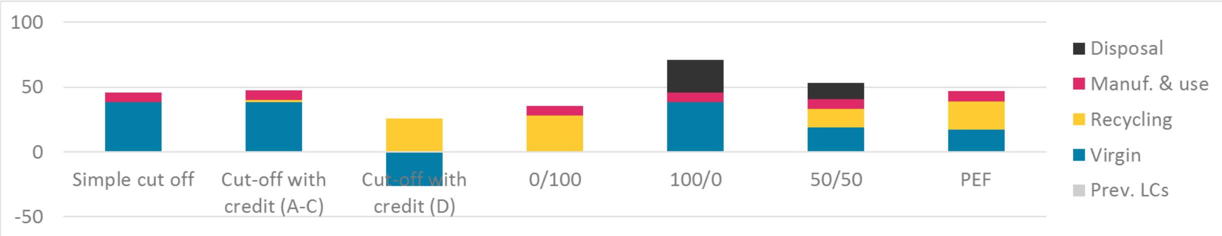

Figure 6.1: Carbon footprint results from the Tetra Pak case study on beverage cartons with application of different approaches to allocation at recycling. The results illustrate Case 1: virgin raw material and 10 % recycling at end of life. Unit: g CO_2 eq. per package.

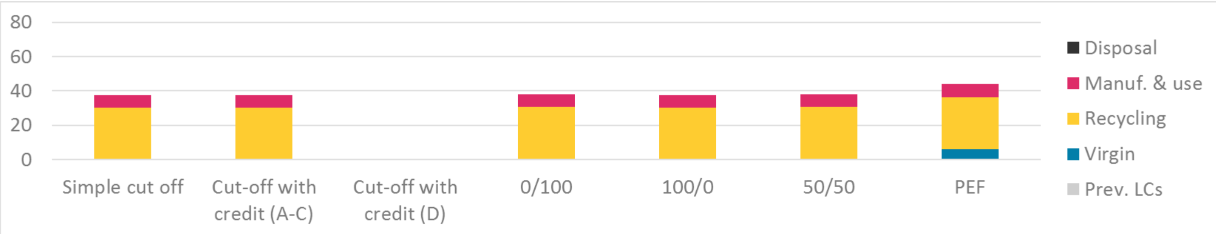

Figure 6.2: Carbon footprint results from the Tetra Pak case study on beverage cartons with application of different approaches to allocation at recycling. The results illustrate the hypothetical Case 2: 100% recycled content and 100 % recycling at end of life. Unit: g CO_2 eq. per package.

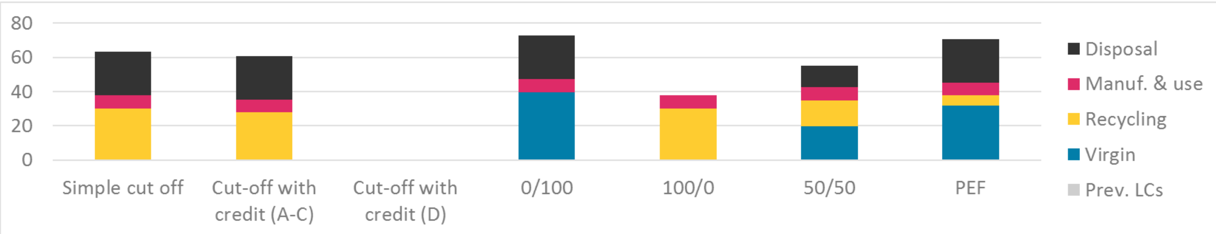

Figure 6.3: Carbon footprint results from the Tetra Pak case study on beverage cartons with application of different approaches to allocation at recycling. The results illustrate the hypothetical Case 3: 100% recycled content and 0% recycling at end of life (incineration without energy recovery modeled as end of life process). Unit: g CO_2 eq. per package.

Observations

The results in Figure 6.1 show that the current beverage carton (Case 1) is quite insensitive to the choice of allocation method. This would be even clearer if the disposal had been modelled with a lower impact (now 'worst case' incineration without energy recovery is modelled). This is likely to be the case in general for products having similar impact regardless of using virgin or recycled content.

When a product system is sensitive to allocation, the choice of allocation approach will, of course, have a large impact. This is important to keep in mind when comparing two product systems, especially if one is sensitive and one is insensitive to allocation. The requirement in the ISO 14044 standard to test important assumptions in a sensitivity analysis, including choice of allocation, is a good way to understand the robustness of results. The challenge is of course when only one allocation method can be included, like for example in environmental Type III labelling or in the PEF methodology.

Modeling in general

The results shown above are in line with results from previous LCAs on beverage cartons.

A general observation is that the calculation tool made available by the project helped the modeling a lot in that the methods had already been translated into functioning models. The interpretation of the different methods had so to say already been done.

Also, looking at several products with varying recycled content and varying recycling rates helped understanding the dynamics of the methods. From looking at the results in Figures 6.1-3 it is easy to understand how the virgin material, recycling process and end-of-life is allocated depending on allocation method.

Relevant

Methods capturing the impact of both recycled content and recycling rate are preferable from a circularity perspective. Of the assessed methods for this case, this would most clearly include the 50/50 and cut-off methods.

Ease of use

The included methods were considered easy to use in general. As mentioned before, having the calculation tool facilitated the modeling a lot.

In fact, having the model ready was a pre-requisite for the PEF modeling. If not, this method would not be easy to use. Also, the fact that the required factors for the PEF formula was publicly available made the modeling possible.

The cut-off with credit requires higher level of data granularity in that both the impact of the collection and recycling process need to be known.

Data availability

The data availability for the beverage carton was good. There is a long history to perform LCAs in the packaging sector which has generated good coverage in LCI databases and in available LCA.

Annex 7. RISE case study on powder-metal product

Patrik William-Olsson and Mats Zackrisson, RISE Research Institutes of Sweden

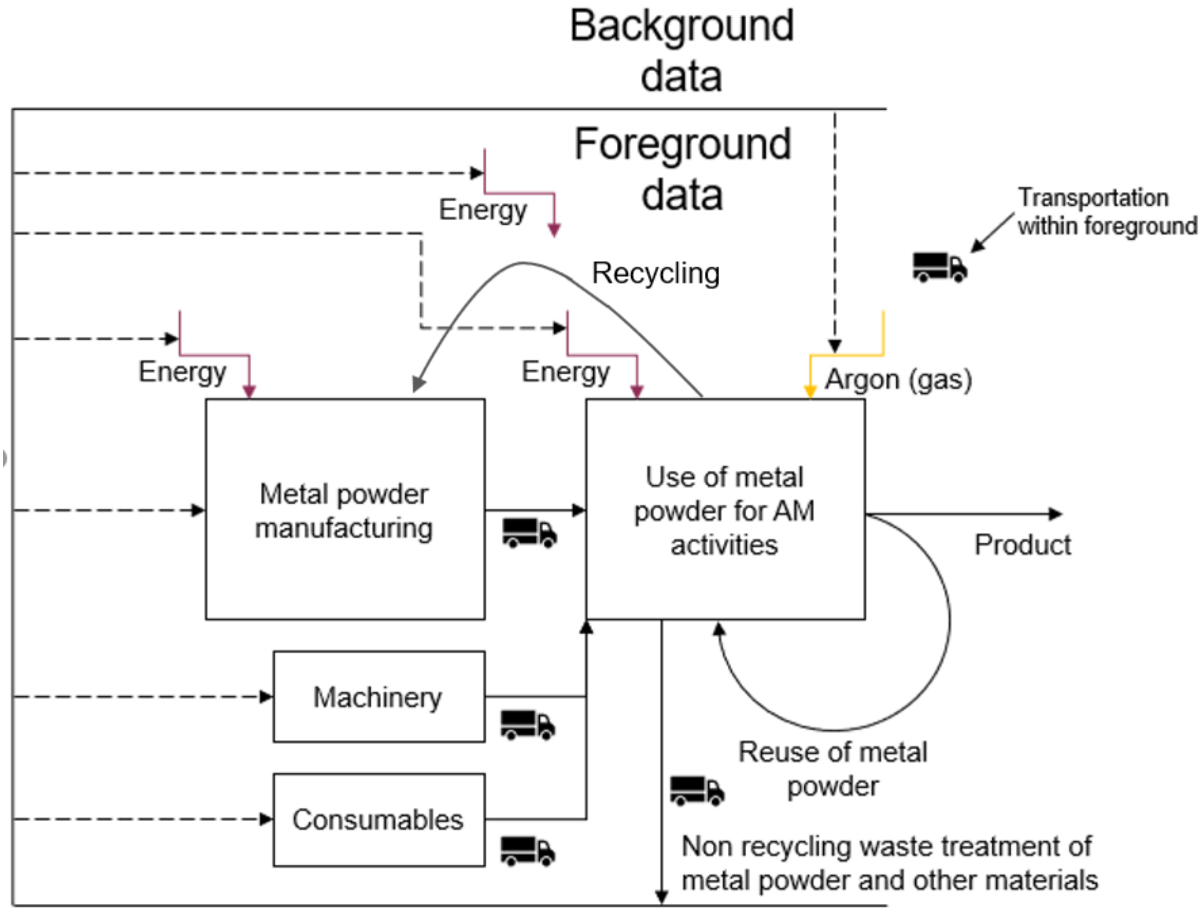

Figure 7.1: System investigated in the case study on a powder-metal product. Note that the product leaves the system and its further fate is not considered in the calculations.

Case study

The case is based on an existing study for internal use in the Manuela project. The results show the climate impact related to the manufacturing of a product with a weight of 106 grams with the additive manufacturing technology. The system is designed from cradle to gate, the waste is limited to that which occurs during production. This means that end-of-life recycling of the product is not included. The powder wasted in production is sent back to smelter for recycling. This loop is considered in the calculations as R_2, see figure below. The percentage of waste going to R_2 is varied as there is no definite answer regarding the recycling rate of the waste metal powder yet. The waste input (R_1) is approximated to an industry average of 55% slightly lower than aluminium cans (60%). The system encompasses metal powder consumption, electricity usage, gas usage, machinery wear, transport and utilization of consumables such as protection gloves and face protection. Only aluminium metal powder has data for recycling in these calculations as R_1 and R_2 can only handle one material at a time. The values that were used for this case is an example of what the environmental impact can look like when using the technology. A figure of the system is presented in figure 1 below. You can read more about the project at the web page: https://manuela-project.eu/.

Results

The results presented above differ depending on the input R_1/output R_2 of recycled material. If the output of recycled material from the production is higher than the input (R_1 55%, R_2 100%), then the impact from 0/100 will be low. If the recycled material input is higher than the output (R_1 55%, R_2 0%), then the impact from simple cut-off and 100/0 will be low. If the recycled input equals the recycled output, then the allocation methods will provide almost identical results with the slight difference emerging due to the powder going to the product being left out of calculations. The 50/50 approach is in between the 0/100 and 100/0 as expected. All other methods could not be used due to lack of data such as quality or other parameters.

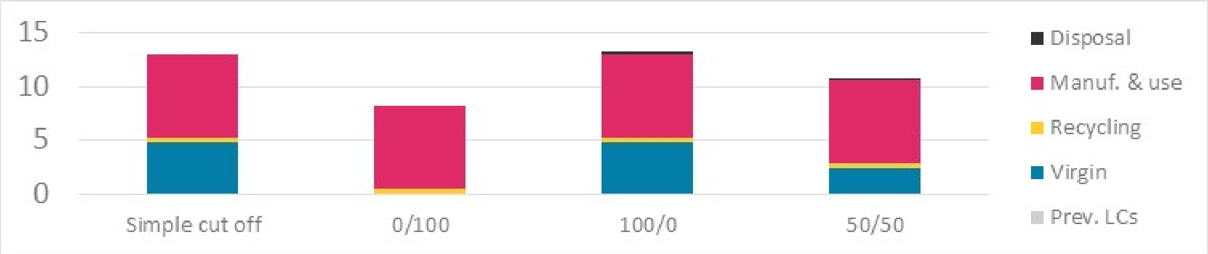

Figure 7.2: Climate change (kg CO_2 eq./product) results from the MANUELA case study on production with additive manufacturing with application of different approaches to allocation at recycling. Recycling input R_1 (55%) < recycling output R_2 (100%); simple cut off, 0/100, 100/0 and 50/50.

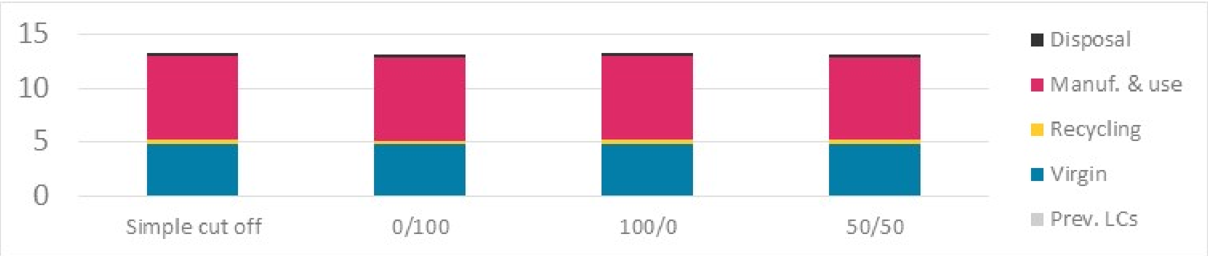

Figure 7.3: Climate change (kg CO_2 eq /product) results from the MANUELA case study on production with additive manufacturing with application of different approaches to allocation at recycling. Recycling input R_1 (55%) = recycling output R2 (55%); simple cut off, 0/100, 100/0 and 50/50.

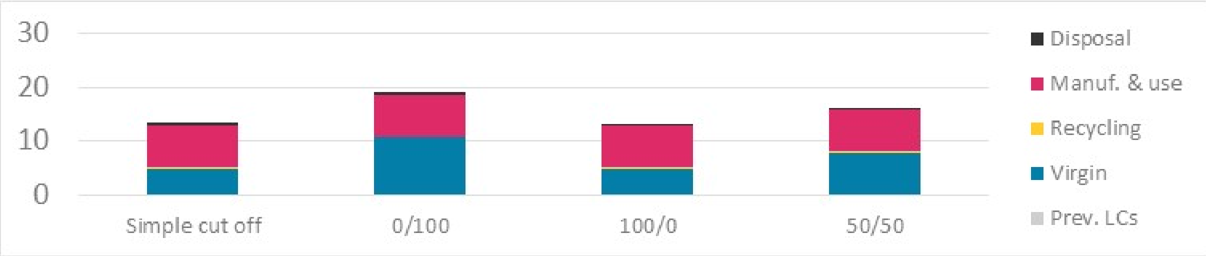

Figure 7.4: Climate change (kg CO_2 eq /product) results from the MANUELA case study on production with additive manufacturing with application of different approaches to allocation at recycling. Recycling input R_1 (55%) > recycling output R_2 (0%); simple cut off, 0/100, 100/0 and 50/50.

Observations

The methods cut-off, 100/0, 0/100 and 50/50 are relatively easy to understand. The other allocation methods (PEF, price elasticity substitution, market price substitution/allocation, etc.) are hard to understand as well as to gather information on.

For the Manuela project, cut-off or 100/0 seems to carry most information and are therefore good options. The use of 0/100 method would risk hiding the environmental impact of virgin production. Cut-off would similarly risk hiding environmental impacts from disposal which would be a problem if the impacts from disposal were large, which is not the case in this case.

Annex 8. KTH case study on concrete

Seyed Salehi, KTH

Case study

Concrete is one of the most used building materials in the world. It is being produced from Cement, aggregates, water and chemical additives. The mixture of these materials is different in different geographical areas, projects etc. but since cement is by far the biggest contributor to the global warming among concrete substances, the amount of cement has a decisive role in terms of carbon emission. After the long lifespan of a construction project, concrete will be demolished and crushed. According to the current wide-spread technology, the aggregates can be recycled and used while the cement cannot be recycled. However, several projects have found new technologies for recycling cement recently, which may become competitive in the coming years.

The basic considerations of this study:

- This case study was conducted by Seyed Salehi, KTH master student, as a part of his thesis work using the calculation tool of the project.
- The transportation distances are assumed to be 100 km in all stages of the lifecycle.
- Depending on a wide range of factors that should be calculated through concrete tests, the quality of the concrete from recycled aggregates can vary. There are various technologies to produce recycled aggregates in different countries from South Korea to Netherlands, but the average current technology has been used to evaluate the quality. Hence, in this study, the average reduction of compressive strength with water-to-cement ratio 0.55 has been used. [1]
- The energy use of the end-of-life processes are all from a study conducted for Boverket, Sweden. [2]
- The case study on concrete mix is based on an EPD from Skanska for concrete in Stockholm area. [3]
- Concrete at landfills absorbs CO2. An uptake equal to 2% of the emissions from cement production has been assumed for the first 100 years in the landfill. [4]
- For the Price-elasticity substitution method, the elasticity indicators are calculated from an average between 2005 and 2016, based on a market report. [5] However, calculating accurate variables need economic models based on more detailed data.

- Virgin aggregate price is according to NCC company [6], recycled aggregate price is according to the Maserfrakt website [7] and cement price is an average of different cement prices according to the website www.byggmax.se.

Results

Figure 8.1 presents results from the case study on concrete.

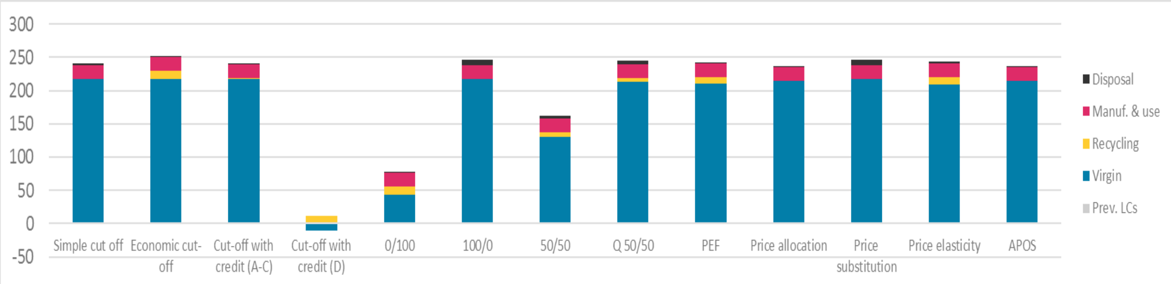

Figure 8.1: Climate change results from the case study on 1 m³ concrete with application of different approaches to allocation at recycling.

Concrete is a long-lasting material which is usually in place for at least 50 years. The methods 0/100 and 50/50 show dramatically lower values than other methods, mainly because of the fact that they put burdens from cement production on the shoulders of the user of recycled concrete. Even though this user hardly has any use for the cement in the recycled concrete. If there is a demand for 50/50 studies, the quality-adjusted 50/50 will be fairer to be used in this context.

Since the current widely used technologies do not recycle cement _biggest carbon dioxide emitter_ the recycling credits and benefits are not that high while cement production has huge environmental impact. This is the main reason that cut-off with credits (Module D) is small comparing to other figures and cut-off with credits (Modules A-C) shows a slightly higher number than the simple cut-off method. A possible key technology in the future will be recycling of cement that will reduce clinker production, resulting in a greener recycled-based concrete.

Another major problem of concrete is landfilling. Landfilling of concrete requires massive areas in some countries. However, eliminating concrete disposal by reusing the aggregate will not be encouraged if we just look at the global warming potential. Hence, it is recommended to have other environmental impact categories in the future studies.

Observations

The material-based methods that do not involve economics are easy to use and the data are available using LCA results. The Circular Footprint Formula is the trickiest method among the studied method mainly because of Factor A. The market for concrete itself, recycled cement and the quality of the recycled cement are all unclear in the far future. Since A determines the shared responsibility of the burdens between first and second user, it is controversial to be used for a long-lasting material like concrete. The price-elasticity approach is a good economic approach comparing to other economic approaches while it considers real market but calculating or finding elasticity indicators are not easy. Having an online database that updates elasticity indicators can make the method easier to use and more accurate.

The data regarding aggregate sourcing from the mines can be varied depending on the context. The average data for Europe is used in this study, which can be justifiable while aggregates does not emit a considerable amount of the total concrete emissions. The results of this study are for the exact concrete mix of the case study. Different concrete mixes with varies methods of procurement and geographical area will have different results. The overall pattern in the results, however, is robust and can be considered as a good general source of information.

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Annex 9. Volvo case study

Anton Jacobson and Mia Romare, IVL Swedish Environmental Research Institute

Case study

This case study focusses on evaluating batteries from Volvo's electrical bus. The case has evaluated the environmental impact of using the battery for a second life and how the environmental impact differs depending on the choice of allocation method.

Batteries in buses need to have a high quality and state of health to cope with the demand of a bus. When the battery is taken out from a bus the "state of health" of the battery is still ~80 % which mean that it is still fully functional for other application than for Volvo buses.

Volvo is interested in how they can get more function out of the environmental impact from producing and using battery in their vehicles by selling or renting the used batteries to other applications as a "second life".

In this case the second life application is energy storage in a housing cooperative in Göteborg. They use the batteries to store energy from solar panels which generate energy during the day and is mainly consumed during the evening.

The case we have looked at covers 14 second life batteries, with 80 % state of health (SOH) and lifetime of 10 years in the second application. It is assumed that they are replacing batteries with 100% SOH and 20 years lifetime.

- The data used in this case study comes from previous LCAs for Volvo busses, measurements from the implementation of the second use case and assumption regarding a potential market for second life batteries.
- The data regarding price have been estimated since the market for this application is not developed. The analysis has been made on a "best" resp. "worst" case scenario, with the expertise of Volvo Group. Since the price influences only 3 of the studied methods we have not presented the comparison between the price estimates.
- The evaluation and case study have been performed by IVL.

Results

Figure 9.1 presents the results from the case study on second life batteries for the "best case"-scenario (high price for second life batteries) because this represent a more interesting future scenario.

The result is shown from a Volvo perspective (in contrast to for example the second users' perspective) and thus it represents the environmental impact that is allocated to Volvo and the first application of the batteries. Between the first- and second life applications a simple quality check will be performed on the batteries. They will also be transported a short distance within the City of Göteborg. Also, these stages are included in the allocation, but where shown to have a very small impact compared with the production and use phase.

Figure 9.1: CO_2 eq. results from an LCA of a battery in an electric Volvo bus, which, after use is reused for another purpose.

Observations

Overall, the work with the methods was found straight forward on a conceptual level, but there were several parameters which were hard to understand. This was in part due to the nature of the parameters but perhaps also to a larger extent for this case since we use the methods designed for modelling recycling as methods for modelling reuse with second life benefits. One needs to have a deep knowledge of the product or material being studied, but also the methods to be able to use the methods easily. This combination may sometimes be hard to achieve due to that the LCA expert has knowledge of the methods may not always have insight into the function of the product or material.

Specific observations regarding this case:

1. Some methods can introduce extra work that extends the scope of data collection significantly. Example: Data on avoided virgin production. Methods:

- Cut-off with credit
- Quality-adjusted 50/50
- CFF
- Market-based substitution

- Price elasticity

Explanation: If the user of the second life battery would have chosen another type of battery, we would have to do an LCA of the other type of battery to get the correct number of "avoided upstream". This compared to simply assuming that the second life batteries replace new batteries of the exact same type.

2. There is a risk for double calculation regarding the degradation of function in the system. Example: Quality factor(s). Methods:

- Cut-off with credit
- Quality-adjusted 50/50
- CFF
- Market-based substitution

Explanation: We discussed how we wanted to represent the quality losses of the battery (going from 100% to 80%). We can use both a quality factor like price difference or state of health or focus on the actual physical number of batteries needed. In a first trial we represented quality both ways, which ended up in double calculations for some methods. The simple conclusion was that the user needs to make sure to understand the parameters involved in the chosen method to avoid double calculation of for example quality loss.