



**Evaluation environnementale des options de recyclage  
selon la méthodologie d'analyse de cycle de vie :  
établissement d'une approche cohérente appliquée aux  
études de cas de l'industrie chimique**

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Dieuwertje Schrijvers. Evaluation environnementale des options de recyclage selon la méthodologie d'analyse de cycle de vie : établissement d'une approche cohérente appliquée aux études de cas de l'industrie chimique. Chimie analytique. Université de Bordeaux, 2017. Français. NNT : 2017BORD0555 . tel-01532008

**HAL Id: tel-01532008**

**<https://theses.hal.science/tel-01532008>**

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THÈSE PRÉSENTÉE  
POUR OBTENIR LE GRADE DE

**DOCTEUR DE**  
**L'UNIVERSITÉ DE BORDEAUX**

SCIENCES CHIMIQUES  
CHIMIE ANALYTIQUE ET ENVIRONNEMENTALE

Par Dieuwertje SCHRIJVERS

**Evaluation environnementale des options de recyclage selon la  
méthodologie d'Analyse de Cycle de Vie :**

Etablissement d'une approche cohérente appliquée aux études de cas de l'industrie  
chimique

**Environmental evaluation of recycling options according to the  
Life Cycle Assessment methodology:**

Establishment of a consistent approach applied to case studies from the chemical  
industry

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# **Titre : Evaluation environnementale des options de recyclage selon la méthodologie d'Analyse de Cycle de Vie : Etablissement d'une approche cohérente appliquée aux études de cas de l'industrie chimique**

**Résumé :** La modélisation du recyclage - et l'allocation en général - est un sujet très débattu dans le domaine de l'analyse du cycle de vie (ACV). Cette thèse a pour objectif le développement d'une approche scientifique et cohérente pour la modélisation du recyclage en ACV afin de fournir des informations pertinentes aux entreprises. Ainsi, un cadre systématique est établi pour catégoriser les procédures d'allocation existantes en fonction de l'objectif de l'ACV et de l'approche attributionnelle (ACV-A) ou conséquentielle (ACV-C). Une revue critique des directives officielles a montré qu'aucun d'entre elles ne recommande des procédures d'allocation conforme à ce cadre. L'approche d'imputation basée sur un schéma axiomatique qui explicite toute hypothèse subjective a été identifiée comme la méthode la plus pertinente pour l'ACV-A. Dans le cas de l'ACV-C, le ratio entre le prix du marché du matériau recyclé et celui du matériau primaire substitué est présenté comme un nouvel indicateur pour identifier si le recyclage permet de substituer la production de matériau primaire ou d'éviter son traitement en tant que déchet. Les processus qui sont affectés par une demande changeante pour un produit sont identifiés avec un diagramme de boucle causale, qui inclut également les stocks anthropiques comme un nouvel élément dans l'ACV-C. L'application des procédures d'allocation est démontrée par une étude de cas portant sur le recyclage des éléments de terres rares (ETR) des lampes fluorescentes. Les deux approches d'ACV fournissent des informations différentes et utiles aux entreprises.

**Mots clés :** Analyse du Cycle de Vie, Recyclage, Industrie chimique, Modélisation, Impacts environnementaux, Éléments de terres rares

# **Title : Environmental evaluation of recycling options according to the Life Cycle Assessment methodology: Establishment of a consistent approach applied to case studies from the chemical industry**

**Abstract :** Modeling of recycling – and allocation in general – is a heavily debated topic in the Life Cycle Assessment (LCA) domain. This thesis aimed to find a coherent scientific approach to model recycling in LCA that provides relevant information to companies. Existing allocation procedures are captured by mathematical formulas and linked to an LCA goal and an attributional or consequential approach in a systematic framework. A review of official guidelines showed that none of them provides recommendations on allocation that is consistent with this framework. A partitioning approach was identified for attributional LCA (a-LCA). This approach is based on subjective assumptions, which are made explicit by axioms. In consequential LCA (c-



LCA), the market-price ratio between the recycled and substituted primary material is introduced as a new indicator to identify whether additional recycling substitutes the production of primary materials or avoids waste treatment. The processes that are affected by a changing demand for a product are identified by a causal loop diagram, which also includes stockpiling as a new element in c-LCA. The application of the allocation procedures is demonstrated by a case study of the recycling of rare earth elements (REEs) from used fluorescent lamps. The a-LCA indicated that recycled REEs are more sustainable than primary REEs. The c-LCA showed that recycling is environmentally beneficial as long as the REEs are used in fluorescent lamps that substitute less energy-efficient halogen lamps. This demonstrates that both LCA approaches provide different but useful information for companies. Suggestions are given for policy measures when the market situation does not stimulate environmentally beneficial behavior. It is recommended, among other options, to extend the causal loop diagram of c-LCA to include additional mechanisms, such as rebound effects.

**Keywords :** Life Cycle Assessment, Recycling, Chemical industry, Modeling, Environmental impacts, Rare earth elements

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**Institut des Sciences Moléculaires**

[CYVI Group, 351 Cours de la Libération 33405 Talence]

## Acknowledgements

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The work of this PhD has been conducted in the Cyvi group at the Institute of Molecular Science in Bordeaux with the financial support of Solvay and the French National Association for Technical Research (CIFRE Convention No. 2013/ 1146). During my PhD, I have had the support of many people, to whom I would like to express my gratitude.

First of all, I would like to thank my supervisor Professor Guido Sonnemann for the great opportunity to do this study. I am very grateful for all the opportunities that he gave me to develop myself, by giving me both helpful guidance and freedom in conducting this work and involving me in a few other projects. Especially the chance to participate in multiple conferences and workshops, such as to go to Japan for the Ecobalance Conference 2016 was very much appreciated.

Many thanks go out to the 3E team of Solvay, especially to Jean-François Viot, Françoise Lartigue-Peyrou, Alain Wathelet and Guy-Noel Sauvion. Their time and feedback were indispensable to move this work in the right direction. Jean-François greatly helped me to formulate both problems and solutions, which led to the refinement of the work. His time and engagement has been very valuable and much appreciated. I thank Françoise for all her help with the case study on rare earth elements and, together with the rest of the 3E team in Lyon, for hosting me during my internship at the Solvay Research and Innovation Center in Lyon. Furthermore, I thank Alain Wathelet for his help with the case study on PVC. I also thank Chrystel Francisoud of GIE AIFOR for her support during the PhD.

I would like to thank Manuele Margni, Tomas Ekvall, Philippe Garrigues, Jean-François Viot and Philippe Roux for their valuable time by participating as members of the jury of my PhD. It is an honor that you agreed to be part of this process.

The feedback of Bo Weidema and Philippe Loubet on earlier versions of Chapters 3 and 4 of this thesis enabled me to greatly improve the work. Furthermore, I thank Koen van Woerden for solving the first-order linear recurrence relation (Equations E2 and E3 of Chapter 3). I thank Reinout Heijungs for pointing me in the direction of the axiomatic approach.

Karine, Eskinder, Michael and Amandine, you gave me a warm welcome in the Cyvi group. Karine, thank you for all your help with basically everything. Tea time is not the same anymore since you left the group. Amandine, you have helped me a lot with my integration in Cyvi, ISM and the French culture and language. You have been a real connector of people and it is thanks to you that I have also met some great people at C2M. Guillaume, Matthieu, Juan, Camille, Lili, Martin, Yannick, Susanne, Yannick, Tomo; I've really enjoyed having lunch, going to the pub and playing board games with you guys.

My dear Cyvi colleagues, it has been a great pleasure to work with you. Alice, Julien, Raphael, Thibaut; keep up the good work Making Cyvi Great after 6 pm! Edis and Amélie, I'm looking forward to more parties in the Cyvi house. Some colleagues only stayed for a short time but have managed to contribute greatly to the atmosphere. María, Luciano, Charlotte, Kalai, Steffi; it was great to have you in Bordeaux. Baptiste, thanks for sharing the office with me. It was very nice to be able to share the struggles of writing the thesis with you. Shared sorrow is half a sorrow! Raphaël, I'm very grateful for your help with the French translation. Philippe, thank you for your help with the French abstract and your support during my PhD. Your feedback has always been very valuable and your BBQs are great too!

Paul, Benjamin, Philip, Uyxing, Wiljan, Kars, Thérèse, Nicole; thanks for dragging me now and then out of the PhD bubble into the rest of the world where there is sport, theater, the beach, pubs and sausages and Obatzda for breakfast.

Mimi and Shishi, thank you both for your great support. Your friendship has been very valuable for me. It has been great to be able to relax with you, to have fun with you and to know that you guys can always cheer me up.

Ik ben al mijn vrienden in (en uit) Nederland erg dankbaar voor hun betrokkenheid en vriendschap, ook al is de afstand groot. Het IPG, het IPG-plus, de Kodama's, Dubbelzinnig, de Harderwijk-gang; bedankt voor jullie gastvrijheid op de momenten dat ik weer eens in Nederland ben. Also Kelsey, even though we didn't see each other during my PhD, I'm very happy that we are still in touch and the pictures of Forrest always make my day. Hinde, Yohan en ik gaan proberen om eindelijk eens langs te komen op de camping! Hilde, Willemijn, Rianne, Willemien, Wilke, Koen, Lisette en Jorrit, het was super dat jullie op bezoek zijn geweest in Bordeaux. Ik vind het erg jammer dat we elkaar zo weinig hebben gezien en ik zal mijn best doen om daar verandering in te brengen! Willemien en Lisette, jullie digitale gezelschap was altijd een welkome afleiding van het werk.

Papa, mama en Floor, ik waardeer het erg dat jullie zoveel interesse tonen in mijn ontwikkelingen in Bordeaux. Jullie aanmoediging en begrip betekenen veel voor me. Floor en Riba, ik hoop dat jullie snel op bezoek komen! Je suis également très reconnaissant pour le support et l'accueil chaleureux que j'ai reçu de tous les membres de ma belle-famille.

But most of all, I am tremendously grateful for the support I got from Yohan, mon petit ourson. Jij was mijn grootste steun. You cooked for me, you traveled with me and you helped me to conquer countless hurdles, imaginary or not. Knowing that you have my back is the greatest encouragement.

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## Executive summary

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Modeling of recycling is a heavily debated topic among experts working with Life Cycle Assessment (LCA). In LCA, the potential environmental impacts of a product are assessed, based on the function that the product provides. Due to recycling, a single product might be able to provide multiple functions: the product system becomes multifunctional. Besides recycling, also co-production results in a multifunctional product system. As the topic of interest in LCA is a single function, an allocation procedure is required to identify which environmental impacts are related to which co-functions of the product system. Some guidance on applying allocation is given in the ISO 14044 standard, although it is often argued that this guidance does not take different LCA goals into consideration. Developments in the scientific domain have shown that an LCA can be conducted to identify for what impacts a product is accountable – which requires an attributional approach – or to identify what impacts are caused by the additional demand for a product. The latter LCA goal is served by a consequential approach. Attributional and consequential LCA studies require different allocation procedures, which is not acknowledged in the guidance in ISO 14044. Numerous guidance documents have been developed by (inter-)governmental institutes and their recommendations on allocation are very divergent. Furthermore, these recommendations are criticized by industrial sectors. It is argued that recycling of metals requires a different allocation procedure than the recycling of materials with a different market situation, such as plastics. However, different types of materials could be used for similar applications. Industry recognizes the need for clear guidance to model recycling in LCA that can be applied to different material types. The research question of the PhD study is therefore formulated as follows:

*What is a coherent scientific approach to model recycling in Life Cycle Assessments, and how can this approach be applied to produce relevant environmental information that supports objectives of industrial interest?*

With the purpose to answer this research question, the thesis presents first a state of the art of allocation procedures for recycling in LCA. These allocation procedures have been categorized in a systematic framework, which has been used as a basis for a critical review of guidelines. The partitioning method in attributional LCA and the substitution method in consequential LCA have been further enhanced to increase consistency between recycling and co-production and among different product groups. The systematic framework and the enhanced allocation procedures have been tested on several case studies of Solvay: 1) recycling of rare earth elements from fluorescent lamps, 2) the use of new scraps in the production of polyamide 6 and 3) recycling of PVC from electrical cables into recycled PVC compound. The case study on the recycled rare earth elements is presented in the thesis. The main findings of the work conducted in the thesis are summarized below.

### Development of a systematic framework for modeling of recycling in LCA

A coherent and science-based systematic framework of modeling procedures for recycling is developed in Chapter 3 (Figure 1). To this end, first, a more detailed state of the art is presented of allocation procedures for recycling. In the search for a coherent allocation approach, consistency is strived for between different multifunctionality situations – i.e. recycling, energy recovery, and co-production. Besides the differentiation between attributional and consequential LCA, it is considered that LCA studies can be conducted in order to assess the environmental performance of a process – i.e. a process-oriented LCA – or to identify the impacts related to the demand for a product in a product-oriented LCA. The allocation procedures are expressed by mathematical formulas that

demonstrate the different mechanisms of each procedure. The systematic framework shows that there is a relevant difference between process-oriented and product-oriented LCAs for the application of allocation. Partitioning is applied in a product-oriented attributional LCA, and substitution – either by the end-of-life recycling method, the waste mining method, or the 50/50 method – in a product-oriented consequential LCA. The application of partitioning and substitution can be avoided in a process-oriented LCA by the use of system expansion. Hence, the allocation procedure is dependent on different elements of the goal and scope definition of the LCA: the perspective, the reason to conduct the study, the intended application and the definition of the functional unit. Based on these elements, archetypes of LCA goal and scope definitions are formulated in Table 1 that represent typical LCA research questions that are supported by the framework.

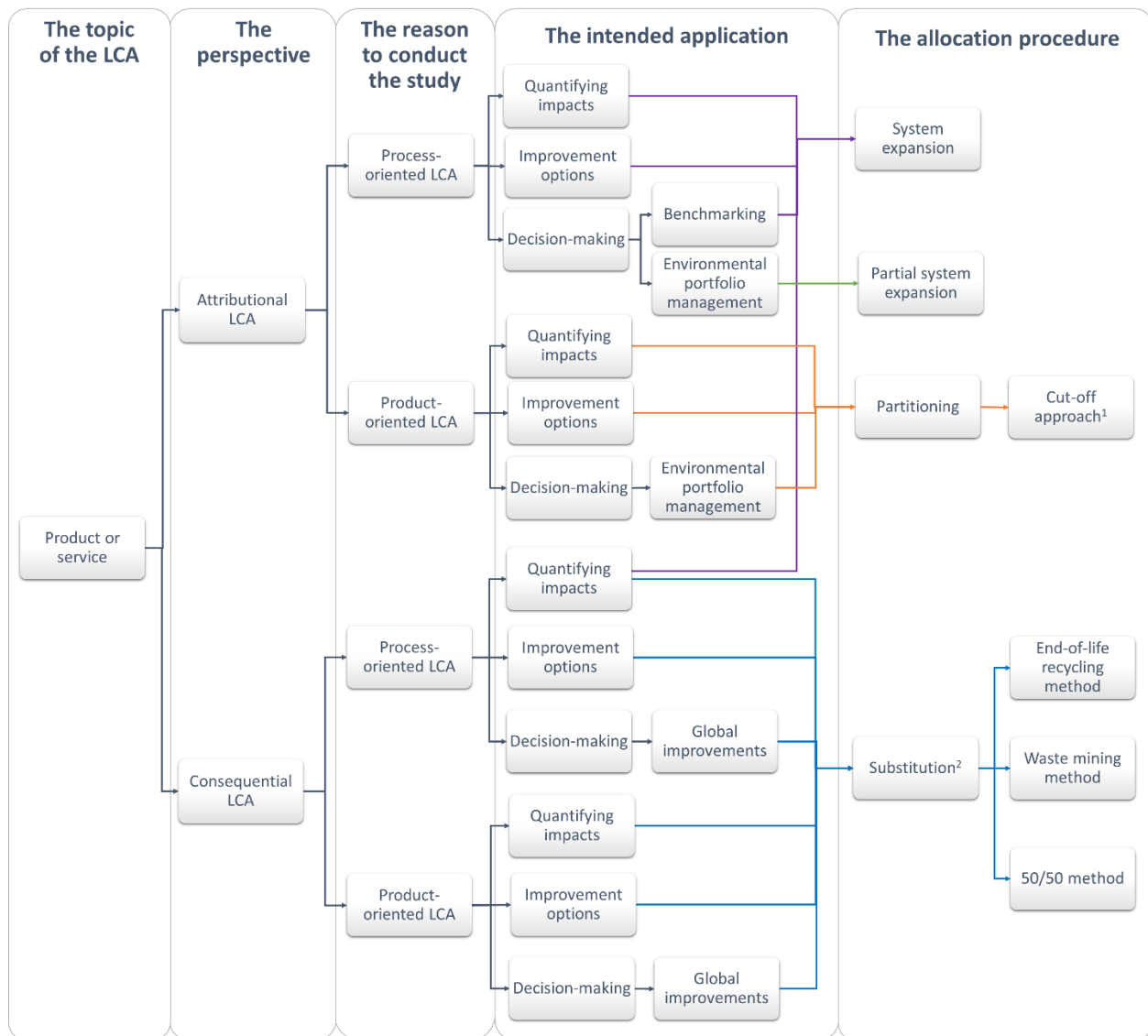


Figure 1 Systematic framework for consistent allocation in LCA. <sup>1</sup>The cut-off approach is considered as a specific case of partitioning where 100% of the impacts are attributed to the primary product. <sup>2</sup>The market situation of the material indicates which substitution method is applied

Table 1 Building blocks of archetypes of LCA goal and scope definitions. The terms represented by  $\alpha$ ,  $\beta$ , and  $\gamma$  are used in the archetypical goal and scope definitions as defined in the box below

Item of the goal and scope definition	LCA approach		Building blocks of archetypical goal and scope definitions
The perspective of the LCA	Attributional LCA	$\alpha$	$\alpha$ : Accountability for impacts
	Consequential LCA		$\alpha$ : Consequences on global impacts
The reason to conduct the study	Process-oriented LCA	$\beta$	$\beta$ : The production / valorization / treatment
	Product-oriented LCA		$\beta$ : The demand
The functional unit	Partitioning / Substitution	$\gamma$	$\gamma$ : The topic of the LCA
	System expansion		$\gamma$ : The topic of the LCA and additional functions

#### Archetypical LCA goal and scope definitions

- **Quantifying environmental impacts:**
  - o What is/are the  $\alpha$  of  $\beta$  of/for  $\gamma$ ?
- **Identifying opportunities for improvement:**
  - o How can we decrease the impacts of  $\beta$  of/for  $\gamma$ , in order to decrease the  $\alpha$ ?
- **Decision-making:**
  - o *Global impacts/Benchmarking:* Does  $\beta$  of/for  $\gamma$  have (a) lower  $\alpha$  than its alternative?
  - o *Environmental portfolio management:* Is [stakeholder] accountable for lower impacts due to the  $\beta$  of/for  $\gamma$  than in an alternative situation?

Identify current consistency gaps and unresolved problematics with regard to the modeling of recycling in LCA

The systematic framework of Figure 1 is limited in the sense that it does not give guidance in *how* partitioning can be applied in an attributional LCA, and how the choice can be made between the three substitution methods for different types of materials in a consequential LCA. This choice is dependent on the market situation of the material, which could be quantified by price elasticities. The use of price elasticities is limited, due to the fact that they are difficult to calculate. They might not be available for the material under study, they can be aggregated, or referring to a different time horizon than the scope of the LCA study. Furthermore, existing literature referred to multiple recycling loops and stockpiling as missing elements that should be considered in an allocation approach.

Numerous (governmental) guidelines are available that provide specific recommendations on allocation. These guidance documents are critically reviewed in Chapter 4 with respect to the consistency of their recommendations with the systematic framework of Chapter 3. None of the guidelines is fully consistent with the framework. Partitioning is rarely proposed to model recycling in an attributional LCA. If substitution is recommended, the market situation of the material is not always taken into consideration. Only the ILCD Handbook proposes the waste mining method for recycled materials that are in low demand. Different types of LCA goal and scope definitions are often not taken into consideration and the goal and scope that are represented by the guideline are seldom described in detail. Often, different allocation procedures are recommended for different types of

multifunctionality situations. Furthermore, some guidelines explicitly apply an attributional approach, while combining this with elements of a consequential LCA. The critical review showed that clear guidance to conduct an attributional and a consequential LCA in a consistent manner is still missing.

#### Enhancement of goal-dependent allocation procedures

Figure 1 shows that there is a relevant difference between process-oriented and product-oriented LCAs for the application of allocation. Partitioning and substitution can be avoided in a process-oriented LCA by applying system expansion. However, this is not possible in a product-oriented LCA. Therefore, the approaches for partitioning and substitution were found to require further development to consistently conduct a product-oriented LCA.

The approach of partitioning in attributional LCA is given a scientific basis in Chapter 5 by the application of an axiomatic method. From this, “allocation at the point of substitution” with economic allocation is identified as the partitioning approach that represents best a product’s accountability for impacts. With a new equation, it is demonstrated that the partitioning approach can calculate the inventory of a product that has been recycled multiple times before while differentiating between the recycled content and the end-of-life recycling rate.

In Chapter 6, the new market-driven substitution method is introduced for consequential LCA in which the market-price ratio  $A$  between the recycled and the substituted primary material allows to indicate whether additional recycling substitutes the production of primary products or avoids waste treatment. The market-price ratio allows operating as a switch between the end-of-life recycling method, the 50/50 method, and the waste mining method. Furthermore, the market-price ratio aids in identifying suitable substitutes and indirect downstream effects.

Furthermore, in Chapter 6 a Causal Loop Diagram (CLD) is developed (Figure 2) that can be used as a tool to identify the indirect effects of the supply or demand of a material in consequential LCA. This CLD includes all the effects that are calculated by the market-driven substitution method. The CLD differentiates between determining co-products – e.g. primary products – and dependent co-products, e.g. recycled products. Besides, it is considered that some primary products are only produced as dependent co-products, which are therefore modeled by the market-driven substitution as well.

Dependent co-products for which demand is low are not necessarily treated as waste. Primary dependent co-products are more likely to be stockpiled. Stockpiles are considered – together with waste streams of scraps and end-of-life products - as valuable sources of material. Therefore, anthropogenic stocks are identified as the marginal supplier of dependent co-products for which demand is constrained. The production from anthropogenic stocks is referred to as recycling or “valorization”.

#### Application of the framework and allocation procedures to case studies

The formulation of archetypical LCA goal and scope definitions of Table 1 and the application of the systematic framework of Figure 1 are demonstrated by a case study on the recycling of rare earth elements from fluorescent lamps in Chapter 7. This case study allows to illustrate the application of the allocation procedures “allocation at the point of substitution” and the market-driven substitution method. The attributional case study shows that recycled rare earth elements are accountable for lower environmental impacts than primary rare earth elements. The consequential case study demonstrates that recycling of rare earth elements is environmentally beneficial, as long as these elements will be used in fluorescent lamps in order to replace less energy-efficient halogen lamps.

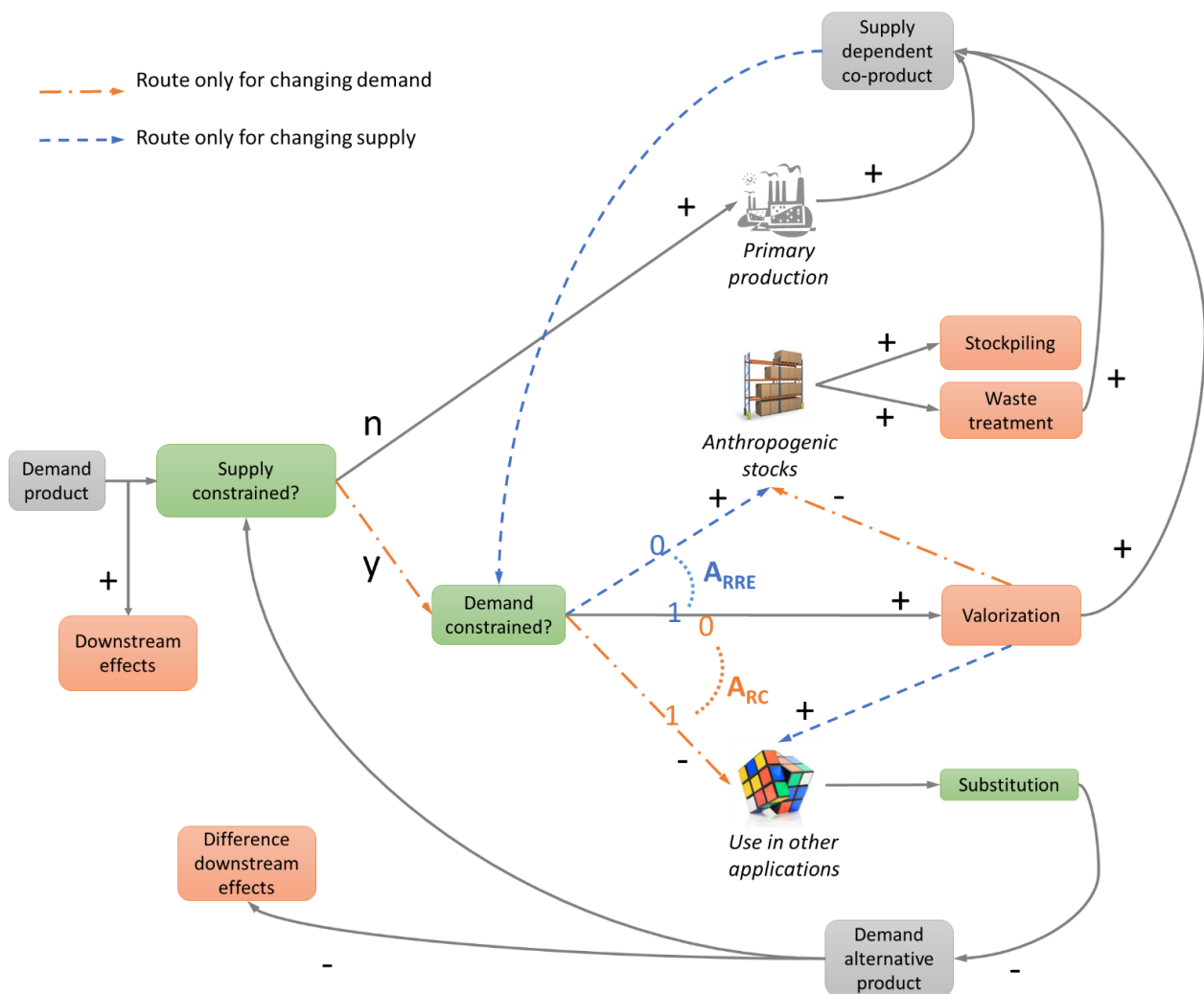


Figure 2 Causal Loop Diagram to identify the consequences of a changing demand for a product in a multifunctional system. Pluses and minuses represent positive and negative feedback mechanisms, respectively. The factor  $A_{RC}$  is calculated by the market-price ratio of the recycled content and the substituted primary material in the current life cycle.  $A_{RRE}$  represents the market-price ratio between the supplied recycled material and the substituted primary material in the subsequent life cycle

### Guidance to industrial stakeholders and policy makers

It is discussed in Chapter 8 that both attributional and consequential LCA provide relevant information for companies. Attributional LCA shows whether the operations of a company are environmentally sustainable. In consequential LCA, the market-price ratio  $A$  allows to indicate whether the recycled content or the recyclability of a product is environmentally beneficial. This information could be used in marketing activities. Consequential LCA furthermore shows similarities with a resource criticality assessment. Therefore, a consequential LCA could indicate whether the operations of a company are sustainable from a socio-economic point of view. Also for policy makers, attributional and consequential LCA are relevant: Consequential LCA shows which products contribute to a more environmentally friendly society. Attributional LCA shows which products are affected by governmental policies. Regulations could be designed such that environmentally beneficial products become more sustainable. Furthermore, the market-driven substitution method can aid to identify whether subsidies could create a market situation that stimulates environmentally beneficial behavior.

## Application of the results of this thesis

The objective of this thesis was to develop a coherent and scientific approach to model recycling in LCA, which produces results that are relevant for companies. This objective has been achieved by the development of a systematic framework of allocation procedures. The choice for an allocation procedure is dependent on the goal and scope of the LCA. The procedures of the framework are further enhanced to allow for a consistent application in all multifunctionality situations of recycling, as well as co-production. The allocation procedures for recycling situations developed in this thesis are found to be coherent, based on scientific principles and provide relevant information for objectives of industrial interest. Furthermore, they are compliant with ISO 14040 and ISO 14044. The systematic framework and the allocation procedures can be applied by LCA practitioners and can serve as inspiration for future guidance documents. The main limitation of the systematic framework is the dependency of the allocation procedure on the defined archetypes of LCA goal and scope definitions.

## Glossary

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Several terms are used in this thesis that can have different interpretations in the LCA domain. The list below could serve as an easy reference to the definitions and interpretations of the vocabulary that is applied in this thesis.

Term	Meaning or definition	Reference in the thesis
Allocation	The act of isolating the functional unit from the additional functions that the product system provides, for example by means of partitioning or substitution. System expansion could also be considered as an allocation procedure, as the additional functions of the product system are integrated into the functional unit.	Chapter 2, section 2.2.2.
Anthropogenic stocks	The marginal supplier of dependent co-products for which demand is constrained. In this thesis, anthropogenic stocks refer to stockpiles of primary materials that are not taken into use yet, hibernating stocks, expended stocks and potentially deposited stocks.	Chapter 6, section 2.1.
Attributional LCA	LCA approach that aims to assess the accountability for impacts of the subject of the LCA.	Chapter 2, section 4.1.
Benchmarking	A comparison of the product system under study with the average production route for all functions that the product system provides could give an indication whether the impacts of the process could be regarded high or low.	Chapter 2, section 2.1.3.
Closed-loop recycling	The situation in which the recycled material that is produced by a product system is used in the same product system as recycled content.	Chapter 3, section 2.3.
Combined production	A situation of co-production in which the production quantities of the co-products are independently variable.	Chapter 3, section 2.1.
Consequential LCA	LCA approach that aims to assess what impacts are caused by the subject of the LCA.	Chapter 2, section 4.1.
Cut-off approach	Allocation procedure in which the recycled product or the waste is considered burden-free.	Chapter 3, section 3.1.4.
Demand constraints	Factors that cause that an additionally supplied product is not absorbed by the market.	Chapter 3, section 3.2.1.
Dependent co-product	A joint product (a product from joint production) for which a change in demand will <i>not</i> affect the production volume of the co-producing unit process (based on Weidema et al. (2009))	Chapter 3, section 3.2.1.
Determining co-product	<i>“A joint product (a product from joint production) for which a change in demand will affect the production volume of the co-producing unit process”</i> (Weidema et al 2009)	Chapter 3, section 3.2.1.
End-of-life recycling rate (RRE)	The amount of material that is collected for recycling/recovery at the end of life divided by the available material after the use phase.	Chapter 3, section 2.2.
Environmental portfolio management	The impacts attributed to the product system under study are compared to impacts attributed to the product system that is displaced, to identify whether a stakeholder becomes more or less responsible for impacts, regardless the functions that are	Chapter 2, section 2.1.3.



	provided. This type of analysis could be used to support claims such as being “100% carbon-neutral”.	
Joint production	A situation of co-production in which the relative output volume of the co-products is fixed.	Chapter 3, section 2.1.
Marginal supplier	The supplier of a product that is most likely to increase its supply with an increasing price for this product.	Chapter 3, section 3.2.
Marginal user	The user of a product that is most likely to decrease its demand with an increasing price for this product.	Chapter 3, section 3.2.3.
Multifunctionality	The situation in which a product system provides – besides the functional unit – additional functions as well, for example due to co-production, recycling or recovery.	Chapter 2, section 2.1.4.
Open-loop recycling	The situation in which the recycled material that is produced by a product system is used in a different product system as recycled content.	Chapter 3, section 2.3.
Partitioning	Sharing the inputs and outputs of a product system between the multiple functions of this product system according to a partitioning criterion, such as mass or revenue.	Chapter 3, 3.1.2.
Process-oriented LCA	An LCA conducted to evaluate the environmental performance of the system from “cradle to gate” as a guide for environmental management (Azapagic and Clift 1999).	Chapter 2, section 2.1.1.
Product-oriented LCA	An LCA conducted to guide environmental management of the entire product system by providing background LCA data for other systems using one of the co-products (Azapagic and Clift 1999).	Chapter 2, section 2.1.1.
Rare earth elements (REEs)	A group of 17 metallic elements, which are considered as a group due to their chemical similarity and behavior, and their appearance as a group in nature (Gupta and Krishnamurthy 2005).	Chapter 2, section 3.2.1.
Recycled content (RC)	The input rate of a recycled or co-produced material compared to the total quantity of material used.	Chapter 3, section 2.2.
Reference flow	<i>“Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit”</i> (ISO 2006a)	Chapter 2, section 2.1.4.
Substitution	Modeling of the indirect effects caused by the additional supply of, or demand for, a dependent co-product.	Chapter 3, section 3.2.
Supply constraints	Factors that cause that the supply of a product is not fully elastic.	Chapter 3, section 3.2.1.
System expansion	The addition of the co-functions of a product system to the functional unit.	Chapter 3, section 3.1.1.
Valorization	Any activity that transforms an intermediate flow that is produced during the production of a determining co-product into a useful dependent co-product.	Chapter 6, section 4.

## Chapter 1: Introduction

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### 1. Development towards clean technologies without shifting the burdens

#### 1.1. Our problematic dependency on energy

The world is facing numerous challenges these days. Wars in unstable regions have mobilized millions of immigrants. However, even more people can be expected to relocate due to forest fires, water scarcity or flooding, failed harvests due to droughts or heavy rainfall, spreading diseases, and so forth. Climate change is happening. This is fortunately acknowledged by 195 countries, which all have agreed to reduce their greenhouse gas emissions to keep global warming within the limits of 2 degrees Celsius during the 21<sup>st</sup> session of the Conference of the Parties to the United Nations Convention (COP21 2015). One of the main causes of climate change is our dependency on fossil fuels, which might be equally identified as one of the causes of instability in several regions in the world.

Great efforts are needed to create a more sustainable way of living. The Dutch philosopher and journalist Rob Wijnberg advocates – unfortunately in Dutch – that the root of the solution of many of the world's current problems lies in the complete shift to renewable energy (Wijnberg 2016). Not only would this transition reduce our greenhouse gas emissions, renewable energy – e.g. solar energy – is becoming increasingly affordable (Farmer and Lafond 2016; Obama 2017). A global, decentralized availability of cheap and clean energy could enable people to guard themselves against the effects of climate change.

Fossil fuels – coal, oil, and gas – are used to generate electricity, but are also directly used as a fuel. However, the renewable energy sources that are mostly considered as alternatives for fossil energy essentially produce electricity (Armaroli and Balzani 2011). Moving towards an electricity-powered world requires large adaptations in our energy systems. Fuels provide great capacities to store energy, which is still an unresolved issue of electricity producers. We need to develop smart grids and batteries that can manage the mismatch between the supply and demand of electricity (Armaroli and Balzani 2011). Furthermore, applications that have relied on fuels, such as cars, need to be adapted to be able to use electricity.

It is not possible to supply our total energy demand from renewable sources, especially if energy demand is growing at the same rate as it is now. This would require an installation of 10 km<sup>2</sup> of photovoltaic (PV) modules a day between now and 2050 (Armaroli and Balzani 2011). Therefore, besides phasing out fossil-based energy sources, we should increase our energy efficiency. An example is the use of compact fluorescent lamps (CFL) or LED lamps to replace incandescent lights. CFL and LED lights do not only convert electricity into light in a more efficient way than incandescent lights, but they also have a longer lifetime. To replace 22 incandescent lamps only three CFLs or 1 LED lamp are needed, while electricity use can be reduced by 75% for CFLs and up to 90% for LED lights (Navigant Consulting Inc. 2012).

#### 1.2. Shifting the problem from energy use to resource use

While we move towards an energy-efficient society relying on renewable energy, we run into new problems. Modern technologies rely on a more sophisticated palette of materials than classic technologies (Armaroli 2015). For example, CFLs and LED lamps require more metals – both in weight and in variety – than incandescent lamps. Although incandescent lamps need a relatively high quantity of tungsten and nickel, CFLs and LED lamps require a higher quantity of antimony, copper, iron, lead,

mercury, phosphorus, zinc, barium, chromium, gallium, gold, silver and rare earth elements for phosphors than incandescent lamps (Lim et al 2013).

There are several issues related to this increased resource use. First of all, the content of several of these metals in the lamps would classify end-of-life CFLs and LED lamps as hazardous waste (Lim et al 2013). Consumers of incandescent lamps are used to throw the lamps away in household trash. This should be prevented for the hazardous energy-efficient lamps, which therefore require active collection and treatment programs. Secondly, several of these metals can be classified as scarce, precious or critical (Lim et al 2013) and their extraction is not free of environmental problems (Elshkaki and Graedel 2014; Schulze and Buchert 2016). This is further illustrated by the example of rare earth elements (REEs). In fact, all the examples mentioned earlier – wind and solar energy, electric vehicles and energy-efficient lighting – use rare earth elements (Guyonnet et al 2015).

Gross energy requirements and global warming potentials of REEs mining and refining are higher than common metals, such as copper, bauxite, and steel, due to depleting ores (Weng et al 2016). REEs can be distinguished between “light” and “heavy” elements, according to their molecular weight. Light REEs (LREEs) are mostly found in bastnäsite and monazite clays, and their extraction is often associated with elevated levels of radioactive thorium and uranium. Other problems related to REE mining are a significant use of chemicals, the production of solid and liquid wastes and gaseous and particulate emissions, water consumption and land use (Long 2015). To extract 1 ton of REEs from ion-adsorption clays – which mainly produce HREEs –, 300 m<sup>2</sup> of vegetation and topsoil are removed, 2000 ton of tailings are disposed of, and 1000 t of wastewater containing ammonium sulfate and heavy metals is produced (Yang et al 2013). The change of landscape results in an increased frequency and magnitude of flooding during storm periods. As a consequence, ion-adsorption mining results in permanent loss of ecosystems, soil erosion, air pollution, loss of biodiversity and human health problems (Yang et al 2013).

Problematic waste treatment and environmental impacts during the primary extraction of materials are not uniquely for metals. For example, in 2014, worldwide 311 million tons of plastics were produced, for which a quantity of oil was needed that is equivalent to almost 2000 large oil tankers (PlasticsEurope 2015). In the same year, 30% of the post-consumer plastic in Europe ended up in landfills (PlasticsEurope and EPRO 2016), while landfilling is generally found to be the most impactful disposal option (Laurent et al 2014).

### 1.3. The need to recycle

Recycling provides a solution to both environmental problems related to waste treatment and the primary extraction of materials. The recycling rate of plastics is already 30% in Europe has increased by 64% over the past ten years (PlasticsEurope and EPRO 2016). However, the recycling rate of REEs is currently very low; UNEP (2011) reports rates below 1%. Solvay opened – with financial support from the EU – a recycling facility for REEs from waste phosphorous powder from used fluorescent lamps (Solvay 2012). However, due to current low prices for primary REEs, the recycling facility will shut down again (Sud Ouest 2016).

UNEP (2013) acknowledges that recycling is mainly an industrial economic activity. As long as recycling is economically beneficial, it will happen. If recycling is unprofitable, policymakers must create incentives to stimulate the recycling operations that are most efficient (UNEP 2013). Incentives can be created in several locations in the recycling chain: from stimulating design for recycling to the purchase of recycled materials. Machacek et al. (2015) argue that market mechanisms and legislative drivers were key elements that made the recycling of REEs from lamps by Solvay initially operational. Existing legislation about the collection of energy-efficient lamps and the removal of mercury made the waste

stream of used phosphors easily accessible (Machacek et al 2015). Machacek et al. discuss the potential societal and environmental benefits of additional legislation that also requires recycling this phosphorous powder – which is most often landfilled.

Policy measures can only be supported if there are strong indications that recycling is indeed environmentally beneficial. Recycling processes can cause environmental problems as well, especially considering the increased material complexity of modern technologies. In our efforts to develop cleaner technologies, we should prevent that the avoided impacts during the use phase of a product will take place after all during the extraction of raw materials or the recycling processes. If we try to decrease our dependency on fossil fuels from unstable regions, we should avoid becoming dependent on other countries for our resource use. Furthermore, we should avoid that burdens shift from one environmental problem – e.g. climate change – to another, for example, water use or loss of biodiversity. In short, we need a methodology that assesses the environmental benefits of one technology compared to another, considering all life cycle stages and a wide range of environmental problems.

### 1.4. Life Cycle Assessment

Environmental consciousness is becoming more and more mainstream, related to the introduction of concepts such as Sustainable Development, the Circular Economy, Cradle-to-Cradle and Industrial Ecology. Beaulieu et al. (2015) made an overview of concepts, guidelines, and tools that aim to address and avoid environmental problems (Figure 1-1). They show that several of these concepts represent a philosophy, while they are not yet developed as an operational methodology that enables to assess to what extent an economy, company or product adheres to certain principles. An exception is the concept of Life Cycle Thinking (LCT). This philosophy encompasses the consideration of a wide range of environmental problems throughout the whole value chain a product. LCT acknowledges the fact that shifting of burdens between different stages of a value chain or different types of environmental problems must be taken into consideration. The concept of LCT is well defined and operationalized in the methodology of environmental Life Cycle Assessment (LCA). LCA is considered as the most complete “eco-efficiency” tool (Beaulieu et al 2015).

LCA is a methodology to assess and quantify the environmental impacts of a product or a service throughout its whole life cycle, i.e. from the cradle to the grave. The cradle of a product is the moment of primary extraction of natural resources, and the product’s grave encompasses final waste treatment, such as landfilling or incineration. Other life cycle stages that take place in between are manufacturing, distribution, and use. This is schematically depicted in Figure 1-2. The consumption of natural resources and the emission of pollutants to the environment can take place at any life cycle stage of a product. LCA can be applied in a Life Cycle Management (LCM) approach that addresses the environmental performance of the value chain of businesses (Beaulieu et al 2015).

The LCA methodology is standardized by ISO 14040 and 14044 (ISO 2006a; ISO 2006b) and knows four phases: 1) in the *goal and scope definition*, the product or service that is being studied and the purpose of the assessment are described, 2) during the *inventory analysis*, all flows to and from the environment are collected for all life cycle stages, 3) the *impact assessment* categorizes these flows by the environmental problems to which they can be associated, and calculates the potential environmental impacts caused by the flows, and 4) in the *interpretation* phase, the results of the inventory analysis and impact assessment are discussed and interpreted in a manner that responds to the initial purpose of the LCA.

LCA is a multi-criteria analysis in the sense that multiple environmental problems are assessed. Besides global warming, examples of environmental problems that can be considered are the depletion of

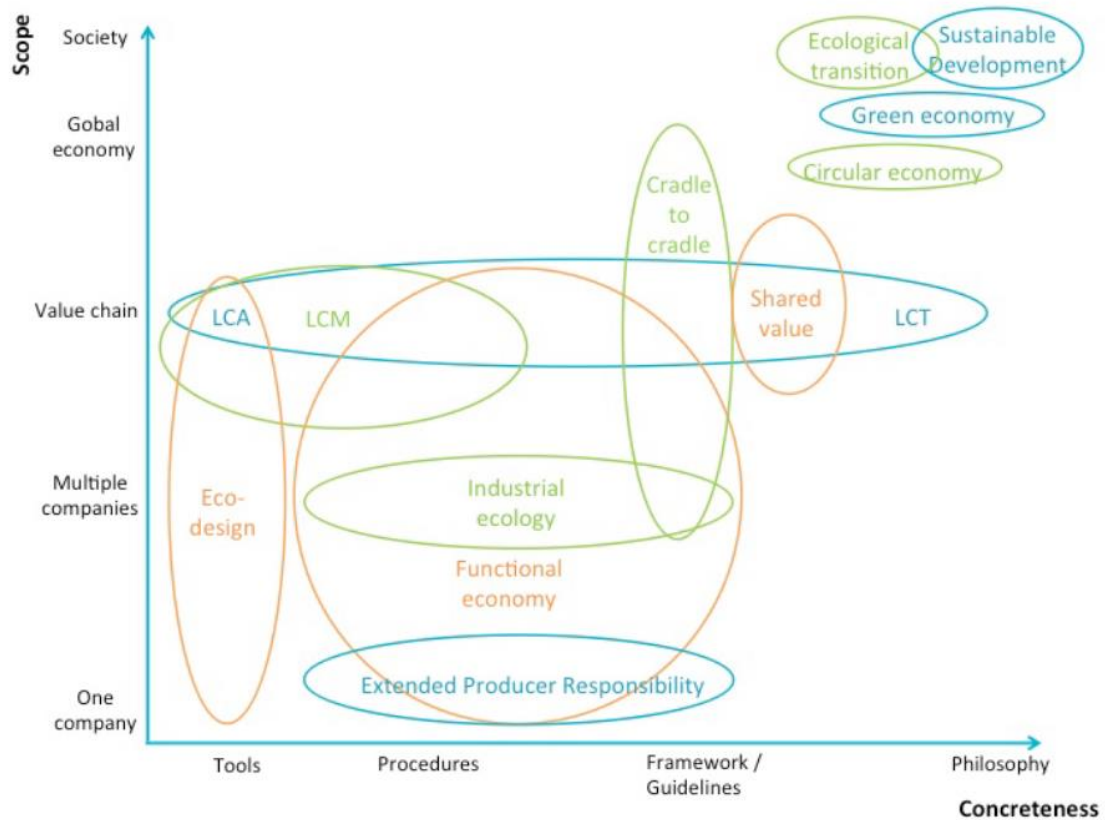


Figure 1-1 Overview of concepts and tools that address environmental problems based on their scope and level of concreteness (Beaulieu et al 2015)

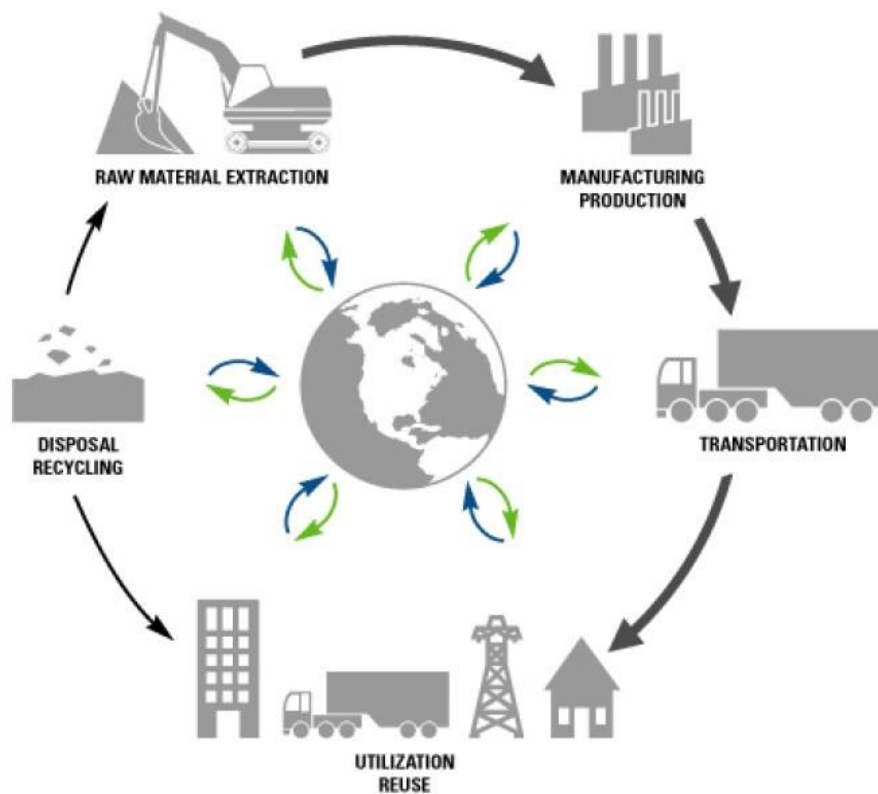


Figure 1-2 A product's life cycle (Wikipedia 2016)

resources, ozone depletion, human toxicity, ecotoxicity, photochemical oxidant formation (smog), acidification, eutrophication and land use (Hauschild and Huijbregts 2015b). The ISO standards foresee several application areas for LCA to understand and address environmental impacts (ISO 2006b):

- *Identifying opportunities to improve the environmental performance of products at various points in their life cycle,*
- *Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),*
- *The selection of relevant indicators of environmental performance, including measurement techniques, and*
- *Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).*

Several of these purposes ask for a comparison between two products, for example, to enable decision-making. Comparisons are facilitated in LCA by its focus on the functionality of a product, rather than a property such as the product's mass. The object of analysis in LCA is, therefore, the "functional unit", which is formulated as the provision of a function in quantitative terms. An example of a functional unit is "20 million lumen-hours of lighting service" in a comparison of an incandescent lamp with a CFL and a LED lamp (U.S. Department of Energy 2013). This enables the comparison of products or services that require different materials, are not equally efficient and have different lifetimes, but nonetheless, provide the same function.

The holistic approach of LCA and the wide application area make LCA a useful assessment tool for consumers, industries, and governments. For example, the European Commission and the United Nations Environment Programme (UNEP) adopt active roles in the development and implementation of LCA (European Commission 2010; UNEP/SETAC Life Cycle Initiative 2011; European Commission 2013). Companies increasingly recognize that environmental consciousness can contribute to the company's image, reduce risks and can even be economically beneficial. Companies will also have to anticipate future governmental policies that will disadvantage environmentally impactful operations (WRI and WBCSD 2011).

These considerations are relevant for companies in general, and for the chemistry sector in particular. The chemistry sector forms the foundation of most other sectors by providing a diverse range of substances that are used in agriculture, pharmaceuticals, consumer care, plastics, mobility (e.g. catalysts), construction (e.g. paint) and electronics (e.g. rare earth elements). The chemistry sector is a large emitter of greenhouse gasses and pollutants and is responsible for a large consumption of energy and water (OECD 2001). While this sector could be associated with many environmental problems, solutions to solve these problems are formulated here as well, such as the introduction of bio-based materials, recycling processes of plastics, and the production of substances that are indispensable for cleaner technologies. These environmental benefits are often only visible outside the perimeter of the chemical industry (ICCA and WBCSD 2013). LCA can be used to assess and communicate the role that the chemistry sector plays in the existence and potential reductions of environmental problems throughout the whole life cycle of a product.

## 2. Problem setting of the thesis

The chemical sector is involved in the production of a large range of products, varying between commodities, polymers, energy, rare earth elements and solvents. Recycling situations are therefore very divergent; from the consumption of recycled materials to the end-of-life recycling of products or materials or the establishment of a new recycling infrastructure, which is the case for rare earth

elements. The diversity of these recycling activities can also be detected in the different ways that recycling situations can be modeled in LCA. Recycling makes a product or a material multifunctional, which makes it difficult to compare to monofunctional products. Multifunctionality can be solved by different allocation procedures. However, allocation is one of the most debated topics in LCA. Although several governmental organizations have attempted to provide guidance on this topic, none of the proposed procedures have been found satisfying by all stakeholders. The metals sector has a pronounced preference for one allocation procedure (Atherton 2007; Eurofer et al 2013), while a different allocation procedure might be more applicable to recycled plastics (AFNOR 2011) or paper (The International EPD® System 2013a). As the practice and implications of recycling vary among sectors, a single method to calculate the impacts and benefits of recycling might not lead to a good representation of these impacts and benefits in all situations. However, if the LCA modeling method is constantly adjusted, much time is lost by identifying the appropriate modeling approach and bias could be introduced by choosing the method that calculates the most favorable results.

For some materials, e.g. polymers, recycling competes with energy recovery as an alternative for waste treatment. Although recycling is often preferable according to certain waste hierarchies (e.g. European Commission (2011)), energy recovery might lead to a higher reduction of environmental impacts. This could be dependent on the quality losses that take place during the recycling process, the second application of the recycled material, the avoided primary energy source, and impacts related to the incineration facility. Similarly, if a waste stream is transformed into a useful material input for a subsequent life cycle, this waste stream could be regarded as a co-product from the previous life cycle. All the material streams that leave the process boundaries and enter nature could potentially be seen as co-products, with a valuable material or energy content. Co-production, energy recovery and recycling all lead to multifunctionality problems that should be solved by an allocation procedure. The boundaries between these situations are however not always clear.

As a large operator within the chemicals sector that produces a wide range of different materials, Solvay recognizes the need for a scientific approach to identifying the appropriate model for recycling situations, based on the principles of LCA. Recycled products and materials are often compared to primary alternatives, so the approach must apply to situations without recycling as well. Considering the broad operating area of Solvay and the diverging types of recycling situations, the approach must be coherently applicable; all materials, sectors and multifunctionality problems should be covered. Furthermore, the model should provide results that are relevant in an industrial context.

Recycling in LCA has already extensively been discussed in scientific literature. We will assess the state of the art in this field and identify the current gaps. These gaps will serve as starting points for the coherent, scientific model for recycling in LCA. Several recommendations have been made by political organisms, which are often based on practical considerations and compromises. We will consider these recommendations while focusing on the scientific basis on which they are founded.

The model for recycling in LCA does not necessarily result in one single method. Several studies indicate that different LCA modeling methods serve different LCA goals (Ekvall and Tillman 1997; Tillman 2000; Thomassen et al 2008). For example, in the case of the recycling process of rare earth elements, it is relevant to identify the current hotspots in the environmental impact of the product, e.g. electricity consumption. There are however several factors that could influence the decision to recycle – factors that can take place in a long term. The European or French electricity mix could change, which influences the impact caused by electricity consumption. Current rare earth mining and refining operations might not be representative of the operations that take place with an increasing demand for rare earths – which is very probable due to recent technology trends, such as renewable energy



and high-tech applications. The impact of an additional demand, focusing on marginal technologies, is generally assessed by a consequential LCA, while LCAs focusing on hotspot identification might be better represented by an attributional LCA (Tillman 2000). The coherent, scientific model for recycling could, therefore, represent a blueprint indicating which method and approach should be used in which situation. This would make the model applicable to all recycling situations of divergent industrial sectors.

To enable an industrial stakeholder to base its decision-making processes on the developed model, the model should be robust and provide relevant results. It should be determined whether all necessary information is provided by the environmental ISO-standardized LCA methodology, or whether we need other modeling tools to provide additional information to reflect the advantages and disadvantages of recycling.

### 2.1. Research question

The research question is formulated as follows:

*What is a coherent scientific approach to model recycling in Life Cycle Assessments, and how can this approach be applied to produce relevant environmental information that supports objectives of industrial interest?*

### 2.2. Objective

The objective of the thesis is to develop a coherent and scientific approach to model recycling in LCA, which produces results that are relevant for companies.

#### *Sub-objectives*

The following sub-objectives serve to achieve the main objective of the thesis:

1. Provide an overview of the state of the art of the modeling of recycling in LCA.
2. Develop a systematic framework of modeling procedures for recycling in LCA.
3. Identify current consistency gaps and unresolved problematics with regard to the modeling of recycling in LCA.
4. Enhance current modeling procedures to increase their consistency.
5. Apply the modeling procedures to case studies of the chemical industry in order to demonstrate and test their applicability and relevance.
6. Identify how the modeling procedures can provide information of industrial interest.

## 3. Thesis outline

### 3.1. Chapters

The thesis is organized as follows:

#### *Chapter 2: Introduction to Life Cycle Assessment and recycling in LCA*

Chapter 2 provides an introduction to the LCA procedure, as standardized in ISO 14040 and 14044. Different LCA modeling approaches are introduced and it is discussed which approach seems most suitable for industrial goals. The problematics around multifunctionality situations and allocation procedures are highlighted (sub-objective 1). Furthermore, from this state of the art, a set of hypotheses is formulated. These hypotheses represent the starting point of the thesis and set the direction of the research that is conducted in the subsequent chapters.

#### *Chapter 3: Development of a systematic framework based on the state of the art of allocation procedures for recycling situations in LCA*



Chapter 3 describes and defines key terms related to recycling in LCA. A state of the art of allocation procedures is provided, and the procedures are expressed in mathematical formulas. A systematic framework is developed that links these allocation procedures to an LCA approach and other elements of the goal and scope definition, such as the reason to carry out an LCA and the intended application. The limitations of the state of the art are discussed which provide the basis of the work in the subsequent chapters (sub-objectives 2-3).

*Chapter 4: Critical review of guidelines against a systematic framework for allocation*

Current recommendations and guidelines are critically reviewed against the framework developed in Chapter 3, with the purpose to identify the consistency of their recommended allocation procedures (sub-objective 3).

*Chapter 5: An axiomatic method to identify one's accountability for impacts in Attributional LCA*

Chapter 3 showed that in attributional LCA, allocation could be applied by a partitioning approach. However, none of the guidelines that was reviewed in Chapter 4 recommends this. Therefore, guidance to apply partitioning in recycling situations is missing. Chapter 5 provides theoretical reasoning with the help of an axiomatic system that supports the application of the partitioning approach "allocation at the point of substitution" in attributional LCA (sub-objective 4).

*Chapter 6: The market-price ratio as a new indicator for demand constraints in Consequential LCA*

The choice between allocation procedures in a consequential LCA is often based on price elasticities. The discussion in Chapter 3 shows that this approach has several limitations. In Chapter 6, the market-price ratio between the recycled material and the substituted primary material is introduced as a new indicator to identify whether recycling avoids waste treatment or the primary production of a material. Furthermore, stockpiling is introduced as a new element that has not been considered in consequential LCA. A Causal Loop Diagram is introduced that aids in identifying the affected process by a changing demand, taken into account supply constraints, demand constraints, marginal suppliers, marginal users, substitutes and anthropogenic stocks (sub-objective 4).

*Chapter 7: Application of the systematic framework for allocation to a case study on the recycling of rare earth elements from end-of-life fluorescent lamps*

Chapter 7 presents a case study on the recycling of rare earth elements from fluorescent lamps (sub-objective 5). This chapter is divided into three sub-chapters:

- *Chapter 7A: Application of the systematic framework*

In the first sub-chapter, the goal and scope definition of the case study is presented. From this goal and scope definition, it follows that both an attributional and a consequential study are required. The different LCA approaches are applied in the sub-chapters 7B and 7C.

- *Chapter 7B: Attributional LCA on the recycling of YOX from used fluorescent lamps*

The attributional allocation procedure that is developed in Chapter 5 is demonstrated on the attributional case study on the recycling of rare earth elements in sub-chapter 7B.

- *Chapter 7C: Consequential LCA on the recycling of YOX from used fluorescent lamps*

The same case study of Chapter 7B is conducted, but this time a consequential approach is applied with the purpose to demonstrate the allocation procedure developed in Chapter 6.

*Chapter 8: Modeling in LCA for goals of industrial interest – lessons learned from the case studies*

Results from Chapter 7 are interpreted in the context of industry-led LCAs. The relevance of attributional and consequential LCA for industry and potential policy measures to stimulate environmentally friendly behavior in industries are discussed (sub-objective 6).

*Chapter 9: Discussion, conclusions, and perspectives*

The hypotheses are tested and the research question is answered. Recommendations are made for further research.

### 3.2. Annexes

*Annex I: Illustrative examples of allocation procedures*

Annex I refers to allocation procedures that are identified in Chapter 3. It is illustrated how the mathematical formulas of Chapter 3 can be interpreted in a cascade recycling system of three life cycles, in the style of Ekvall and Tillman (1997) and Baumann and Tillman (2004). Furthermore, the interpretation and application of the partitioning approach for multiple recycling loops are demonstrated.

*Annex II: Additional analyses on the attributional case study of Chapter 7B*

Annex II contains a discussion on economic allocation in the co-production process of rare earth elements. Furthermore, an uncertainty analysis is presented on the results of the attributional LCA.

*Annex III: Additional analyses on the consequential case study of Chapter 7C*

This annex provides supplementary information to the consequential case study on rare earth elements of Chapter 7C.

*Annex A: Attributional and consequential case studies on polyamide 6 [Confidential]*

Annex A contains an attributional and a consequential case study conducted on the production of engineering-grade polyamide 6. During this process, polyamide 6 scraps from the textile industry are used as a material input.

*Annex B: Attributional and consequential case studies on the recycling of PVC [Confidential]*

Attributional and Consequential LCAs on the recycling process of PVC are presented in Annex B. This process produces recycled PVC compound of similar quality as primary PVC from wastes of electrical cables and tarpaulins.



## Chapter 2: Introduction to Life Cycle Assessment and recycling in LCA

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### 1. Introduction

This chapter introduces the main aspects of the LCA methodology, as standardized by ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b). The case studies are presented on which an LCA is conducted in this thesis. These case studies represent divergent types of recycling situations and serve as a basis to test and demonstrate the modeling methods of recycling in LCA.

Recent developments in the LCA domain with regard to different LCA approaches – i.e. attributional and consequential LCA – are not covered by the ISO standards. These developments influence how recycling is modeled in LCA, which is, therefore, an ongoing topic of debate. (Governmental) guidelines have attempted to fill the gap between the missing guidance in the ISO standards and the development of attributional and consequential LCA approaches. However, the guidelines converge in their recommendations and not all product sectors agree with the guidance. Furthermore, it is unclear to what extent the recommended allocation procedures serve industrial perspectives. An overview is given on the lack of consensus between the ISO standards, the developments in the scientific field, governmental guidelines, and perspectives of different material sectors. This lack of consensus illustrates the need for more guidance on the modeling of recycling in LCA, which is what this thesis aims to provide. From the state of the art, hypotheses are formulated that provide a direction in which the subsequent research steps are undertaken.

### 2. LCA Framework of ISO 14040/14044

According to the ISO standards, an LCA study is built up by four phases:

1. The goal and scope definition phase,
2. The inventory analysis phase,
3. The impact assessment phase, and
4. The interpretation phase

The interaction between these phases is shown in Figure 2-1. The arrows in Figure 2-1 show that LCA is not a linear, but an iterative process. Results of the LCA phases are used in other phases.

LCA is a systemic approach. This means that product life cycles are considered as product systems which provide a function. An example of such a system is given in ISO 14040 (Figure 2-2). The sub-process of the product system are referred to as “unit processes” and the flows between these unit processes are intermediate flows. The product system can be connected to other product systems via product flows, such as co-products or recycled products. Flows going in or out of the product system are elementary flows if the materials or substances are taken from or released into the environment without previous or subsequent human transformation, respectively. Elementary flows can be taken from or released to water, air, and land. Typical elementary inputs in the product system comprise the extraction of primary material from the earth’s crust, the use of water from oceans and rivers and heat from solar radiation. Elementary outputs comprise emissions to air, such as CO<sub>2</sub> emissions, emissions to water, soil or radiation. Elementary outputs are also man-made products that are not further treated, such as plastic packages ending up in the ocean.

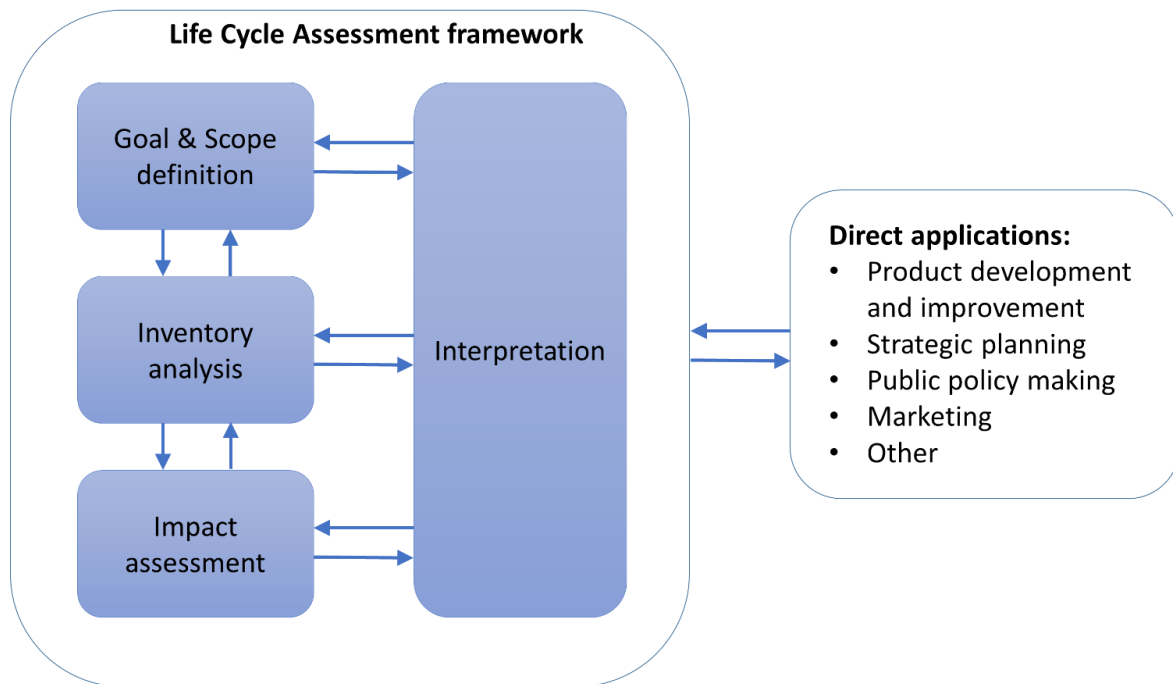


Figure 2-1 Stages of an LCA. Based on ISO (2006b)

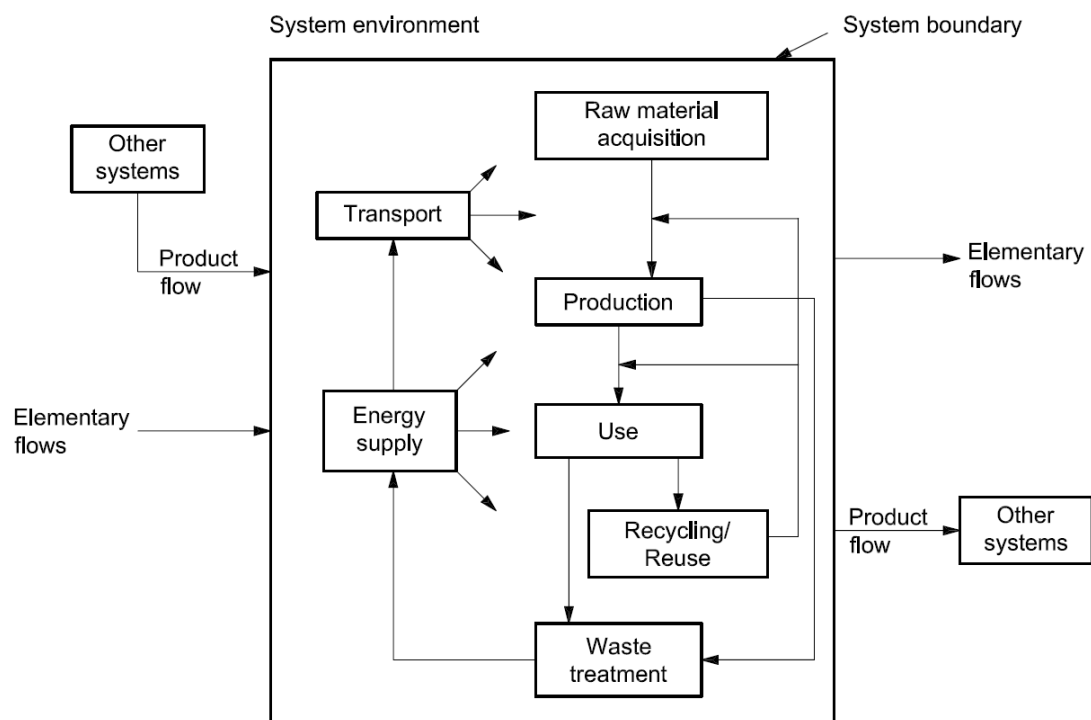


Figure 2-2 Example of a product system for LCA (ISO 2006b)

## 2.1. Goal and scope definition

In the goal and scope phase of the LCA, the topic and the purpose of the LCA study are introduced. The goal and scope phase of the LCA contains several elements, among which the reason to conduct the LCA, the intended audience and the intended application of the LCA results.

### 2.1.1. The reasons for carrying out the LCA

Azapagic & Clift (1999) distinguish two types of goals that can motivate an LCA of a multifunctional production system:

- To evaluate the environmental performance of the system from “cradle to gate” as a guide for environmental management, i.e. *process-oriented LCA*
- To guide environmental management of the entire product system by providing background LCA data for other systems using one of the co-products, i.e. *product-oriented LCA*

Process-oriented LCAs could give relevant information if the aim of the LCA is to evaluate the environmental performance of production sites. This would be interesting for companies that would like to improve the environmental performance of a production process, or that would like to do an organizational LCA of which the production process takes part. Process-oriented LCAs could also provide information for environmental taxation that is targeted at production sites. Product-oriented LCAs can inform downstream users of the products, e.g. for larger LCA studies where one of the co-products is used as an intermediate material or by marketing.

### 2.1.2. The intended audience

The LCA might be conducted for – among others – internal use within a company, for marketing purposes or for communication to governmental institutes. The intended audience influences the level of detail that is necessary for the LCA as well as the presentation of the results.

### 2.1.3. The intended application

The results of LCAs can be used for multiple purposes. The application areas that are most often referred to are:

- **Quantifying the impacts** of a product or process for use in other LCA studies or for environmental labeling. Environmental labeling could show customers or collaborators what the environmental impact of the product is that they consume.
- **Identifying opportunities to improve** the environmental performance of products or processes at various points in their life cycle. A hotspot analysis can identify which products or processes are the largest contributors to environmental impacts. Improvement options could focus on these contributors.
- **Making a decision** between multiple alternative options. The main goal of an LCA is often to compare two alternative products or services that provide the same function. Also, it is interesting to compare the impacts of a product before and after the application of an adjustment that is supposed to reduce the products’ environmental impacts. We could identify several motives for decision-making, among which:
  - o Benchmarking: A comparison of the product system under study with the average production route for all functions that the product system provides could give an indication whether the impacts of the process could be regarded high or low.
  - o Global improvements: The impacts caused by the product system under study are compared to the impacts caused by the displaced product system under study, to identify whether a decision is environmentally beneficial or not.

- Environmental portfolio management: The impacts attributed to the product system under study are compared to impacts attributed to the product system that is displaced, to identify whether a stakeholder becomes more or less responsible for impacts, regardless the functions that are provided. This type of analysis could be used to support claims such as being “100% carbon-neutral”.

#### *2.1.4. The functional unit and system boundaries*

The scope of the LCA demarcates the boundaries of the study. The product system of the topic of the LCA and the functions of this product system are identified. Furthermore, a functional unit is formulated. This describes (one of) the function(s) that the product system provides in quantitative terms. The functional unit is the reference to which all inputs and outputs of the product system are related. If multiple alternatives are compared in the LCA study, the functional unit provides a basis for comparison of different types of products that nonetheless provide the same function. If the product system provides additional functions besides the functional unit, the system can be considered “multifunctional” and an allocation procedure must be applied to isolate the functional unit. This allocation procedure is also described in the goal and scope definition of the LCA.

From the functional unit, the reference flow of the product system can be derived. This flow is often expressed in a quantity of a product that is required from a product system to fulfill a certain function. The system boundaries indicate what unit processes are included in the product system. Ideally, unit processes are included until flows in and out of the product system only comprise elementary flows. Typical elements of a product system that fall within the system boundaries are the acquisition of raw materials, distribution, energy consumption, use and maintenance of products, waste disposal, recycling processes and the manufacturing, use and disposal of ancillary materials and capital equipment that are required to produce the functional unit (ISO 2006b), although capital equipment is in practice not always taken into account (ICCA 2016).

The scope definition furthermore describes which impact categories will be investigated in the study, and the types and sources of data that are used. Also, the required level of detail, assumptions and the limitations of the study are part of the scope. Furthermore, the data quality requirements are identified, which describe – among others – the accepted age, the geographical coverage, the technology coverage, precision, completeness, representativeness, consistency and sources of the data (ISO 2006a).

### **2.2. Inventory analysis**

During the life cycle inventory (LCI) analysis, data are collected to identify the sizes of the elementary flows entering and exiting the product system. During the inventory analysis, it can happen that the goal and scope definition needs refinement due to the increased knowledge about the product system.

#### *2.2.1. Foreground data and background data*

In LCA, often the distinction is made between the foreground and the background subsystems. The foreground refers to all processes that are directly influenced by the functional unit of the LCA study (Azapagic and Clift 1999). Flows to the foreground system are elementary or intermediate flows (Figure 2-3). Intermediate flows are products that are used as input materials which are often supplied via a material market (Azapagic and Clift 1999). Therefore, the production process of these products are part of the background system, and these processes are not always known by the user. Several databases exist that provide LCA inventory – i.e. the elementary flows – for intermediate products in the background system. Gabi and ecoinvent are examples of databases that are often used. It is important that the database is used that corresponds to the goal and scope of the LCA study. For example, a database that includes current processes is of limited use in a study that aims to identify

the hypothetical responsibility for impacts of a product in a future situation, as processes in the database might be outdated in 20 years.

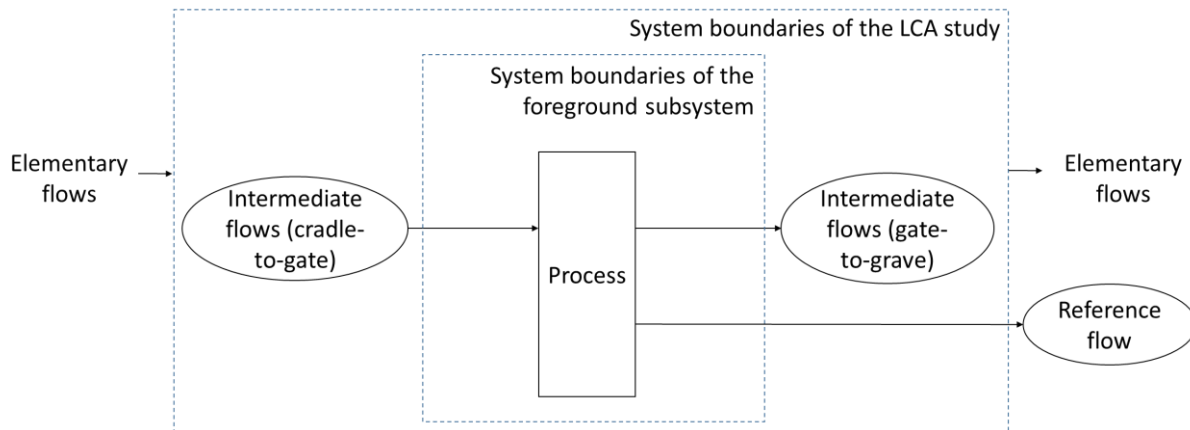


Figure 2-3 Typical system boundaries of a cradle-to-gate study

### 2.2.2. Multifunctionalities

Ideally, the product system provides one function, which is the functional unit, and all elementary flows entering and exiting the product system are allocated to the functional unit. However, most product systems provide multiple functions. Guinée, Heijungs, & Huppes (2004) state that the functional flows of the system must be identified. A functional flow is “any of the flows of a unit process that constitute its goal, viz. the product outflows (including services) of a production process and the waste inflows of a waste treatment process” (Guinée et al 2004). If a process yields multiple functional flows, the process is multifunctional (Figure 2-4). Guinée et al. (2004) identify three typical multifunctional situations:

1. *Co-production: a multifunctional process having more than one functional outflow and no functional inflow*
2. *Combined waste processing: a multifunctional process having no functional outflow and more than one functional inflow*
3. *Recycling: a multifunctional process having one or more functional outflows and one or more functional inflows (including cases of combined waste processing and co-production simultaneously)*

To enable the comparison with monofunctional processes in LCA, the functional unit should be isolated from the additional functions of the product system. Solving multifunctionality problems is referred to as *allocation*. Allocation has however always been one of the most debated issues in LCA, which leads to the need for guidance on how to model recycling in LCA for different products groups.

#### 2.2.2.1. Allocation in ISO 14044

ISO standard 14044 provides a stepwise procedure for applying allocation:

- a) *Step 1: Wherever possible, allocation should be avoided by:*
  - 1) *dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or*
  - 2) *expanding the product system to include the additional functions related to the co-products [...]*
- b) *Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and*



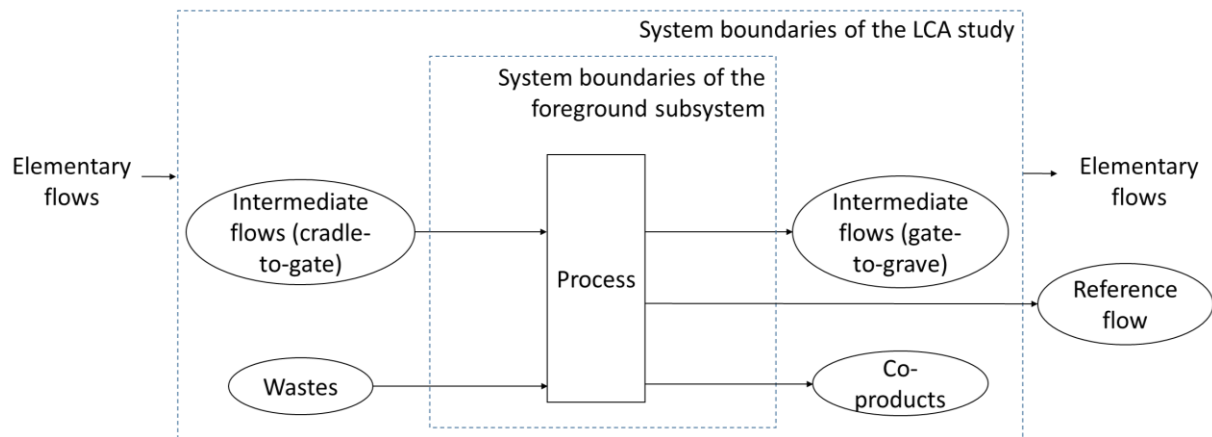


Figure 2-4 Typical multifunctional process that produces the reference flow and co-products, and provides a waste treatment service

*outputs are changed by quantitative changes in the products or functions delivered by the system.*

- c) *Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.*

This procedure is also applicable to recycling situations, although partitioning can be avoided in the case of closed-loop recycling by avoiding primary material. The number of recycling loops should be considered as partitioning criterion as well (ISO 2006a). From this, we conclude that the multifunctionality problem due to recycling is closely related to co-product allocation in general.

#### 2.2.2.2. Recycling, energy recovery, and co-production

Besides the fact that recycling can be considered as a multifunctional process by itself, as stated above, recycling also makes a cradle-to-grave product system multifunctional. A cradle-to-grave product system is typically represented by a linear sequence of life cycle stages as depicted in Figure 2-5. If the end-of-life treatment of a product is a recycling process, the sequence of life cycle stages could become circular, as the end-of-life phase produces a product that can be used as an input material in a subsequent life cycle (Figure 2-6). It could be argued that the product system now provides two functions: one related to the use of the primary material and one related to the use of the recycled material (Figure 2-7). ISO (2006) mentions that *“reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system”*. This implies that the distribution and use phases are generally not considered to require an allocation procedure.

According to the EU Waste Framework Directive and the Roadmap to a Resource Efficient Europe (European Commission 2011a), recycling of materials has the preference over energy recovery. In LCA studies, energy recovery is often considered separately from recycling. However, recycling as such is not always the most environmentally friendly option for a material. In some situations, energy recovery could lead to higher environmental benefits (Bringezu and Bleischwitz 2009). This could depend on the impacts of the recycling process, the quality losses that take place upon recycling and the second application of the recycled material, as well as the recovery efficiency and the incineration technology (Merrild et al 2008).

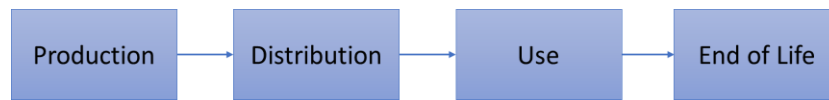


Figure 2-5 Linear representation of a cradle-to-grave product system

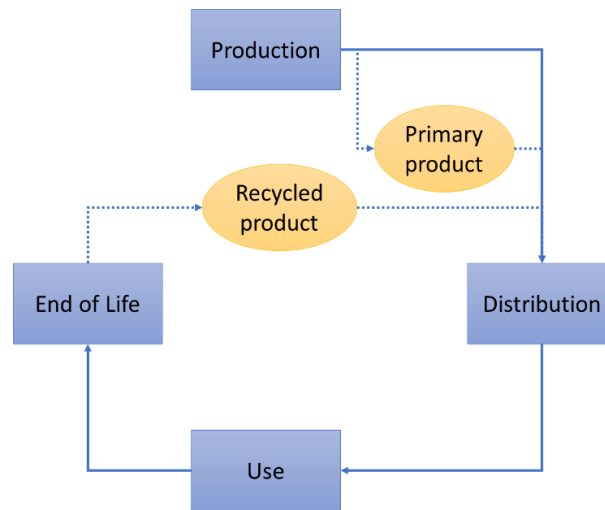


Figure 2-6 Circular representation of a cradle-to-grave product system

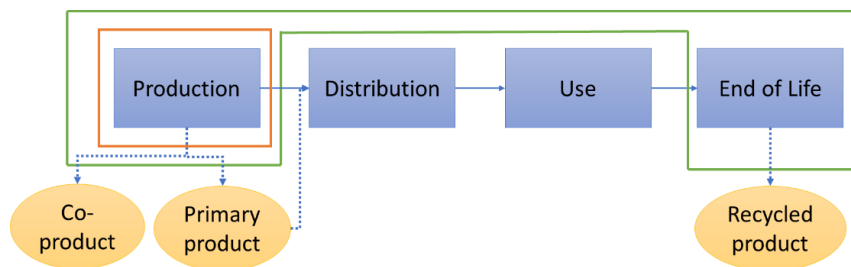


Figure 2-7 Representation of a multifunctional production process due to the production of two co-products (in the orange frame) and a multifunctional product system due to the production of a primary product as well as a recycled product at the end of life (in the green frame)

Similarly, the difference between a recycled product and a co-product can be very small. Co-production was defined above as “a multifunctional process having more than one functional outflow and no functional inflow” (Guinée et al 2004), which is also depicted in Figure 2-7. If a processing waste flow is transformed into a useful material input for a subsequent life cycle, it could be argued that this waste stream is recycled. However, the valorized product can also be considered as a co-product of the process. There is, therefore, no need to consider allocation for co-production and recycling as separate allocation problems (Weidema 2001; Guinée 2002). Applying different allocation procedures to co-products and recycled products even leads to inconsistencies in the system and should be avoided (Weidema 2013). The term ‘recycling’ in this thesis could, therefore, be replaced by ‘recovery’. In further chapters, the term ‘valorization’ is also used to represent any activity that transforms an intermediate flow which might be considered a waste into a useful (co-)product.

### 2.3. Impact assessment

The elementary inputs and outputs of the product system that were identified in the inventory analysis are converted into environmental impacts in the life cycle impact assessment (LCIA) phase. The impacts that are calculated do not represent actual impacts, as this would require full knowledge of the time and location of the impacts and the relations to other product systems. As this information is not available, we calculate *potential impacts*: impacts that could take place considering the

characteristics of the elementary flows. The impact results can therefore not be validated by experiments. However, the calculations are based on scientific environmental models that are internationally supported (ISO 2006a; Hauschild and Huijbregts 2015a). The impact assessment contains several sub-phases, which are described below. The normalization, grouping, and weighting phases are not mandatory. Impact assessment methodologies are continuously evolving, for example by including spatial differentiation. Hauschild and Huijbregts (2015) provide an overview of the state of the art of LCIA.

### *2.3.1. Selection of impact categories, category indicators, and characterization models*

Impact categories that are often considered are climate change, stratospheric ozone depletion, human toxicity, particulate matter formation, photochemical ozone formation, ecotoxicity, acidification, eutrophication, land use, water use and abiotic resource use (Hauschild and Huijbregts 2015a).

Each impact category has a specific category indicator, which enables the quantification of the impacts in a representative unit. For example, the category indicator of climate change or global warming (the nomenclature can vary between impact assessment methods) is “kg of CO<sub>2</sub>-equivalent”. An elementary flow can cause harm to an “area of protection” via several cause-and-effect mechanisms – i.e. the impact pathway. An example of the impact pathway of greenhouse gas emissions (elementary flows) is shown in Figure 2-8. Areas of protection represent values that we wish to preserve, such as Human Health, Natural Resources and the Natural Environment (Hauschild and Huijbregts 2015a). The impact category can represent an area of protection with an endpoint indicator. Alternatively, midpoint indicators can be

identified at any point between the elementary flow and the area of protection along the impact pathway, although this point is ideally the point after which all subsequent effects are the same for all elementary flows (Guinée 2015). The effect on climate change is a midpoint result, which subsequently affects human health or ecosystems at the endpoint level. An overview of the relationship between midpoint and endpoint indicators is given in Figure 2-9. The further the category indicator is identified along the impact pathway, the more uncertainties are introduced in the calculations. Midpoint indicators are more closely related to the elementary flows, while endpoint indicators are easier to understand intuitively, which could facilitate communication to a broader audience.

A large number of different characterization methods is currently available, among which IMPACT2002+, ReCiPe, EI99, CML 2002, EDIP 2003, Swiss Ecoscarcity 2006, etc. (Guinée 2015). Several impact categories are covered by most impact assessment methods. However, the impact categories are not necessarily calculated in the same way. They might not all cover the same elementary flows, and the contribution of the elementary flow to the impacts might vary.

### *2.3.2. Assignment of LCI results (Classification)*

In the classification phase, the elementary flows of the inventory analysis are assigned to impact categories. For example, CO<sub>2</sub> and CH<sub>4</sub> emissions are classified among emissions that contribute to climate change. If a ready-made characterization method is applied, classification (as well as characterization) will be done automatically for a default list of elementary flows (Guinée 2015).

### *2.3.3. Calculation of category indicator results (Characterization)*

In the characterization step, the elementary flows are multiplied with a characterization factor. This characterization factor represents the contribution of this flow to the impact category to which the flow was assigned. The characterization factor enables to express the different elementary flows in this same category indicator. After characterization, the contribution of different elementary flows to one impact category can be summed.

Characterization factors are calculated by characterization models that most often follow this calculation (Hauschild and Huijbregts 2015a):

$$E1. \quad CF = FF * XF * EF$$

The characterization factor ( $CF$ ) is the product of a fate factor ( $FF$ ), an exposure factor ( $XF$ ), and an effect factor ( $EF$ ). These parameters have different meanings in the different impact categories and different impact assessment methods can calculate different types of effects. Table 2-1 shows how the characterization factor of methane differs between impact assessment methods. These difference are related to the consideration of different time horizons by the methods. The contribution of an elementary flow  $i$  to an impact category  $j$  ( $IS$ ) is subsequently calculated as follows (Hauschild and Huijbregts 2015a):

$$E2. \quad IS_{j,i,k,l} = Q_{i,k,l} * CF_{j,i,k,l}$$

Where  $Q$  is the quantity of elementary flow  $i$ . The index  $k$  refers to the location of the emission or extraction, and  $l$  to the environmental compartment (e.g. water, air, soil). From this, the result of each impact category can be calculated, considering all elementary flows in all locations and all environmental compartments (Hauschild and Huijbregts 2015a):

$$1) \quad IS_j = \sum_i \sum_k \sum_l IS_{j,i,k,l}$$

Table 2-1 Characterization factors of carbon dioxide and methane in different impact assessment methods (in kg CO<sub>2</sub>-equivalent/kg)

	Time horizon	CF Carbon dioxide	CF Methane
ILCD 2011 Midpoint+ V1.08	100 years	1	25
IMPACT2002+ V2.12	500 years	1	7.6
ReCiPe Midpoint (E) V1.12	500 years	1	7.6
ReCiPe Midpoint (H) V1.12	100 years	1	25
ReCiPe Midpoint (I) V1.12	20 years	1	72

#### 2.3.4. Calculation of the magnitude of category indicator results relative to reference information (Normalization)

The impacts of each impact category are expressed in different units and can therefore not be compared to each other. It can be difficult to identify which impact categories have a relatively high or a low result in a Life Cycle Assessment. If the impacts of an alternative product system are assessed as well, the impacts can be presented relative to the impacts of this reference system. The impacts could also be compared to the annual impact from an average person, or the impacts measured in a specific geographical region (ISO 2006a; Hauschild and Huijbregts 2015b). This could make the communication of the LCA results easier.

#### 2.3.5. Grouping

Grouping encompasses any type of sorting of the impact categories based on criteria such as global/regional/local impacts or impacts with high/medium/low priority (Baumann and Tillman 2004).

#### 2.3.6. Weighting

It can be difficult to choose between two alternative products if they score differently on different impact categories. For example, one product has a high impact on climate change, and the other product scores high on resource use. In that case, value choices can be introduced that assign weighting factors to each impact category. After weighting, the results of the impact assessment can be aggregated into a single score, which can be compared to the single score of the alternative product.

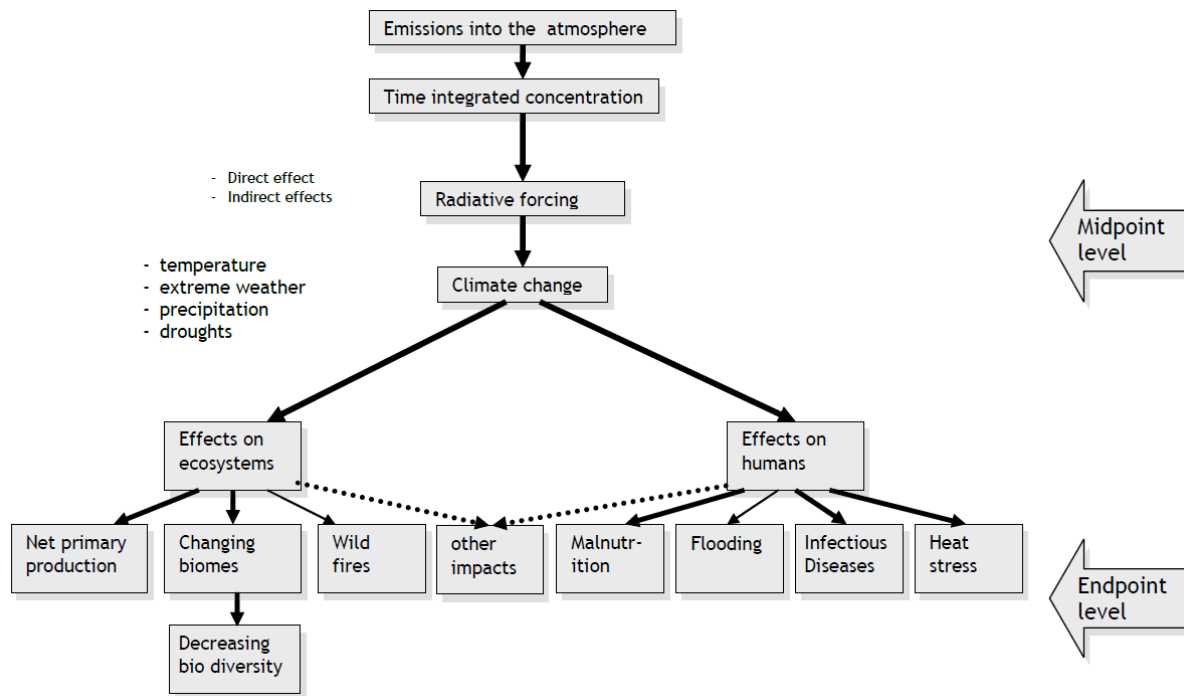


Figure 2-8 Simplified impact pathway for climate change. The thickness of the arrows indicates their relative importance (European Commission 2011b)

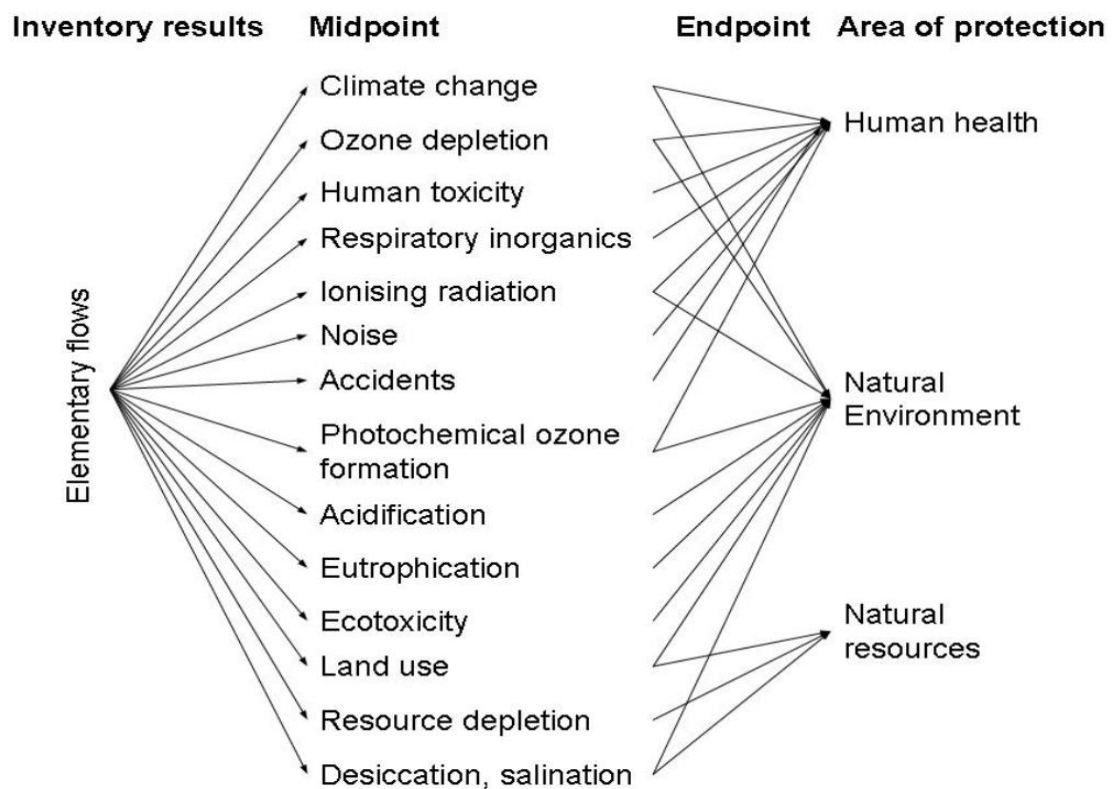


Figure 2-9 Framework relating midpoint impact categories to the areas of protection (European Commission 2011b)

Weighting factors can, for example, be based on costs related to environmental problems (monetarization), governmental policies or panel judgment (Baumann and Tillman 2004).

## 2.4. Interpretation

The interpretation phase of LCA contains the following elements (ISO 2006a):

- *identification of the significant issues based on the results of the LCI and LCIA phases of LCA*
- *an evaluation that considers completeness, sensitivity and consistency checks*
- *conclusions, limitations, and recommendations*

These elements all refer back to the goal and scope definition of the LCA, for example with regard to the limitations that were foreseen and the acceptable data quality level.

Significant issues of the inventory analysis and the LCIA could refer to inventory data or life cycle stages that have a high contribution to impact results or impact categories that appear to have a relatively high score. Several choices that are done in the goal and scope definition can have a relevant influence on the analysis as well. These could refer to the allocation procedures, system boundaries or the intended audience. These choices should be taken into account during the interpretation of the results.

The evaluation considers whether the inventory analysis and impact assessment have reached the level of completeness that is required by the goal and scope definition, in the sense that all necessary data could be collected, and the elementary flows have been characterized for all impact categories that are required according to the goal and scope. The robustness of the results can be verified by a sensitivity check, which encompasses uncertainty and sensitivity analyses. Furthermore, it is identified whether all assumptions, methods, and data are consistent with the goal and scope, for example with regard to data quality, regional and/or temporal differences and the application of the allocation procedures.

Following the identification of significant issues and the evaluation of the assessment, conclusions can be drawn. These conclusions should be in line with the requirements of the goal and scope of the study. Recommendations are done that correspond to the intended application, for example informing a decision to favor one alternative product over another.

The fact that the interpretation phase is strongly connected to the other phases of the LCA illustrates the iterative nature of LCA. For example, if inventory data does not correspond to the initial requirements of the goal and scope definition, the latter can be adapted to make the inventory analysis more acceptable.

## 3. Case studies

### 3.1. Introduction of the case studies

In this thesis, the LCA approach is applied to three different case studies:

#### 1. *Recycling of rare earth elements from end-of-life fluorescent lamps (Chapter 7)*

The rare earth elements (REEs) yttrium, europium, terbium, lanthanum, cerium, and gadolinium are used for phosphors in fluorescent lamps. A fluorescent lamp can emit light due to interactions between mercury and phosphors. An electric current excites the mercury, which subsequently emits UV light. This light is absorbed by the phosphors that re-emit the light in a longer wavelength (Armaroli and Balzani 2011). At the end of life, the used fluorescent lamp is collected to facilitate the removal and recycling of the toxic mercury and the recycling of glass and aluminum (Tan et al 2015). During this process, a powder is generated that contains the used phosphors. This phosphorous powder is



produced as a final waste which is usually landfilled. Solvay developed a recycling process that enables to recover the used rare earth elements from the phosphorous powder.

### *2. Production of polyamide 6 engineering plastics from “new scraps” (Annex A - confidential)*

Polyamide 6 is a plastic that is often used in the automotive sector (PlasticsEurope and EPRO 2016). The plastic is a product of the polymerization of caprolactam. Ammonium sulfate is produced as a by-product of the primary production process of caprolactam. Not only is the caprolactam that is not polymerized recycled in a closed loop, Solvay recycles also discarded caprolactam from a neighboring textile factory. This caprolactam is of insufficient quality for textile while containing all the necessary properties for engineering plastics. The textile industry also produces polyamide 6 scraps during a later production stage. These scraps can be used – after treatment – in a mix with primary PA6 in engineering plastics as well.

### *3. Recycling of PVC from end-of-life products into a recycled PVC compound with virgin-like properties (Annex B - confidential)*

The VinyLoop process recycles PVC waste into PVC compound with similar properties as primary PVC compound (Vandevyver and Thamm 2013). The PVC waste comes from two main applications: electrical cables and tarpaulins. Therefore, this recycling process has elements of “combined waste processing” (see Section 2.2.2.). Besides recycled PVC compound, the two waste flows generate the co-products copper and recycled PET fibers.

These case studies demonstrate the application of the allocation procedures on very divergent multifunctionality situations. They are not only examples of recycling but provide examples of combined waste treatment and co-production as well. Different types of wastes are recycled: products at the end of life, as well as industrial waste. Furthermore, materials of varying industrial sectors are taken into consideration. The case study on rare earth elements is published in this thesis and serves as an example to demonstrate the procedures developed in this thesis. This case study could be regarded emblematic for the modeling difficulties of recycling in LCA. However, additional background information is needed to fully comprehend the relevant considerations in the material market of REEs.

## 3.2. Context on the motivation to recycle rare earth elements

### *3.2.1. Physical availability of REEs*

Rare earth elements (REEs) are a group of 17 metallic elements, which are considered as a group due to their chemical similarity and behavior, and their appearance as a group in nature (Gupta and Krishnamurthy 2005): lanthanum (La), cerium (Ce), neodymium (Nd), praseodymium (Pr), samarium (Sm), europium (Eu), and gadolinium (Gd) are referred to as light rare earth elements (LREE) and terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) are heavy rare earth elements (HREE) (Elshkaki and Graedel 2014). Yttrium is often considered among the HREEs. Scandium is also a REE although not considered among LREEs or HREEs due to the fact that this element does not appear in the same ores as the other REEs (USGS 2015). Similarly, the REE promethium (Pm) does not appear in nature (Gupta and Krishnamurthy 2005) and is therefore not further discussed. REEs are very useful in applications such as, among others, magnets, ceramics, phosphors, electronics and for hydrogen storage (Gupta and Krishnamurthy 2005). Although rare earth elements (REEs) are not necessarily rare – as their name suggests –, their supply is limited by the geology of the deposits, costs of extraction and the basket price of the co-produced elements – i.e. mining is more economic if the ore contains more valuable REEs (Alonso et al 2012).

It is unlikely that REE ores will deplete on the long term (Alonso et al 2012; Habib and Wenzel 2014). The pace of opening of new mines is currently the bottleneck for the short-term availability of the elements. Besides, current and newly opened mines do not necessarily provide the elements that are

in highest demand (Alonso et al 2012). REEs are mostly produced as by-products of other (host) metals, such as iron, titanium, zirconium, and thorium (Elshkaki and Graedel 2014), and the ratio in which the individual REEs are supplied does not correspond to the ratio in which they are demanded. This is referred to as the balance problem (Binnemans et al 2013b). This results in an oversupply of some elements and a shortage of others. REEs are not evenly distributed over the earth's crust. Ores are available over the whole world, but the composition of the ores varies largely. For example, 48% of the global REE reserves is located in China, which however contain 72% of the globally available dysprosium – an element strongly in demand for the application in permanent magnets (Habib and Wenzel 2014). Figure 2-10 shows the distribution of REEs in a number of mines (Elshkaki and Graedel 2014). While cerium, lanthanum, and neodymium represent over 70% of the exploited ores (Alonso et al 2012), other elements that are in high demand are more sparsely distributed. Fulfilling the projected demand for dysprosium by increased production of current mines would lead to a large oversupply of other REEs as well as their host metals (Elshkaki and Graedel 2014).

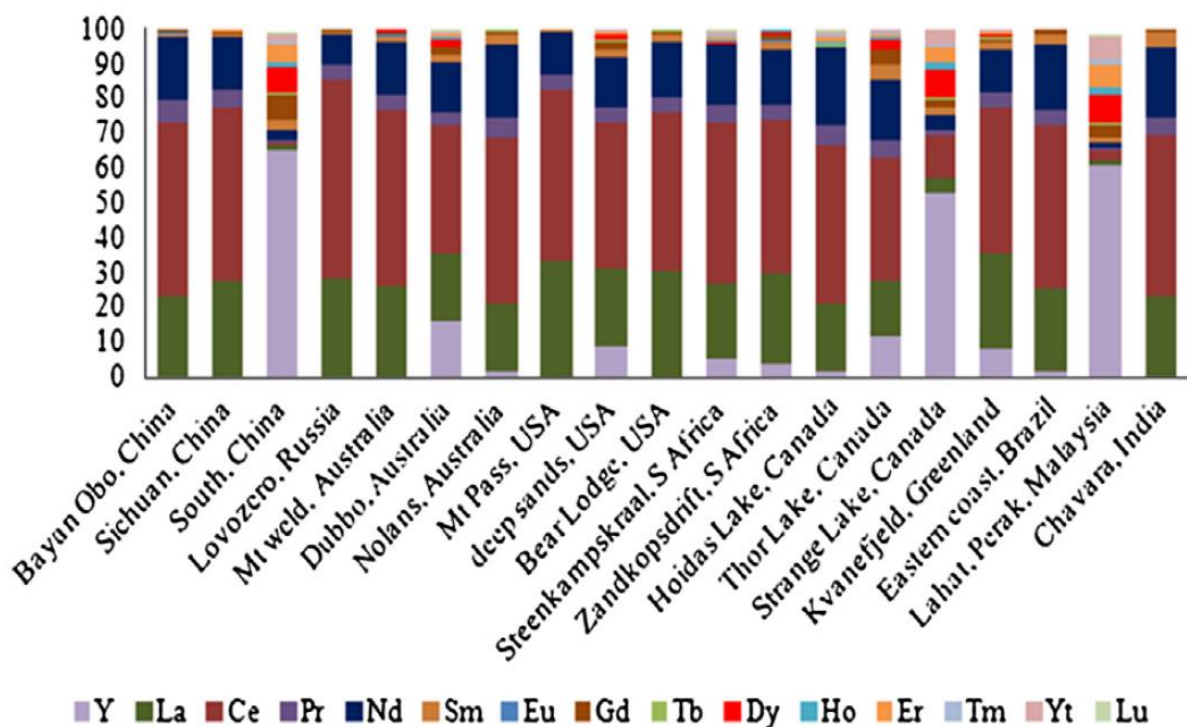


Figure 2-10 The distribution of REEs in several deposits (Elshkaki and Graedel 2014)

### 3.2.2. Developments on the REE market

Even though China only holds 48% of the global reserves of REEs, China is the main supplier with a market share of 87% in 2012 (Habib and Wenzel 2014). This unique monopoly-like position of China and the lack of substitutes for several elements greatly affects the market of REEs. Due to the environmental problems related to the mining of REEs, China decreased export quotas of REEs from 65 000 tons to 30 000 tons in the time period of 2005-2011 (Information Office of the State Council 2012; Guyonnet et al 2015). Prices of REEs peaked in 2011 when some elements became 10 to 20 times more expensive (Guyonnet et al 2015). This had motivated the European Commission and the US Department of Energy to identify several elements as critical, among which neodymium, dysprosium, europium, terbium, and yttrium. Neodymium and dysprosium are needed for permanent magnets, while europium, terbium, and yttrium are mainly used in energy-efficient lamps. Their supply must be safeguarded to facilitate the transition towards cleaner technologies (U.S. Department of Energy 2011;



European Commission 2014a). The high prices for REEs motivated the rest of the world to find alternative sources of REEs, and many initiatives to increase resource efficiency, find substitutes, increase recycling and explore new mining areas have been launched (ERECON 2014; Schlinkert and van den Boogaart 2015). Among these efforts, the Mountain Pass mine in the United States, which shut down in 2002, reopened, and the Mount Weld deposit in Australia increased its production (European Commission 2014a).

The efforts to increase efficient use of REEs and find substitutes after the REE crisis in 2011 led to a decreased demand for the elements (ERECON 2014). As a result, prices of REEs decreased by 80% in 2013 (Guyonnet et al 2015). The drop in prices of REEs had as a consequence that several of the recent initiatives were no longer profitable. The Mountain Pass deposit stopped producing in 2015 (GlobeNewswire 2015). The Mount Weld deposit in Australia is still operating, although without being profitable (Lynas Corporation LTD 2016). Tukker states that investments in REE supply chains should not be stalled until the next crisis when operations become economically beneficial for the stakeholders. It takes years until mines become operational so their response will be too slow (Tukker 2014). Most gains in efficient resource use have been achieved by now and good substitutes are still not available in all applications (ERECON 2014). The fact that REE prices have stabilized does not take away the problems related to supply risks, the mismatch between supply and demand of REEs, the vulnerability to supply restrictions of critical elements and the environmental impacts related to mining.

Recycling of REEs from magnets and fluorescent lamps can provide a solution to these issues (Alonso et al 2012; Binnemans et al 2013a; Elshkaki and Graedel 2014; ERECON 2014; Machacek et al 2015; Schulze and Buchert 2016). Due to the fact that these applications contain several critical elements – neodymium, dysprosium, europium, yttrium, and terbium – primary mining could be avoided and surpluses of elements in lower demand are reduced (Binnemans et al 2013a). Solvay developed a recycling route that enables to recover the rare earth elements from end-of-life fluorescent lamps, which is the topic of the case study of Chapter 7. However, Solvay suffers the same fate as Molycorp: due to the decreasing prices of the elements, the recycling facility will shut down again (Sud Ouest 2016).

### *3.2.3. Complexity of recycling in LCA*

The example of rare earth elements shows that recycling can be motivated by environmental considerations, while at the same time is strongly influenced by interactions at the material markets. Recycling does not only have the potential to avoid the primary extraction of materials; it can also aid in the diversification of a product's supply chain. The status of several REEs as "critical materials" brings an additional dimension of complexity: they are necessary for the transition to cleaner technologies, while there are supply risks and the materials are not easily substitutable. These type of considerations go beyond the LCA framework of ISO 14044. Furthermore, the fact that primary REEs are mostly produced as by-products of other minerals – and always as co-products of each other – shows that the case study represents not only a modeling problem related to recycling but an allocation problem in general.

The case studies of this thesis represent different situations of recycling, which asks for guidance on allocation on a level that is detailed enough to represent divergent cases. Although the ISO standards provide specific and detailed guidance on different phases of the LCA, the standards have limitations. Limitations related to the goal and scope definition and the inventory analysis will be the core topic of this thesis (Figure 2-11). The impact assessment and interpretation phases will not be further discussed in detail.

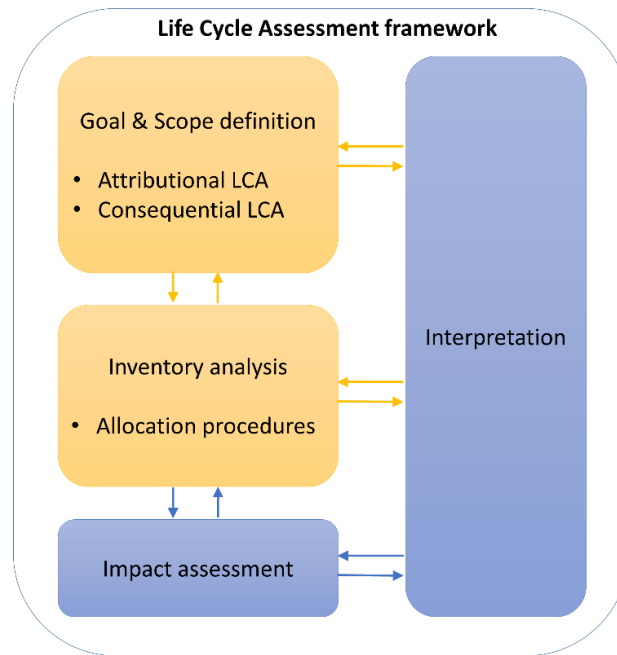


Figure 2-11 Elements of the LCA framework that are studied in this thesis. The relevant life cycle stages in this study are depicted in yellow

#### 4. LCA modeling approaches

The ISO standard provides requirements on the elements that should be included in the goal and the scope definition of the LCA, as described in Section 2.1. Developments in the LCA domain have indicated the existence of various types of LCA goals, which would require different modeling procedures. Tillman (2000) proposed a distinction between retrospective, accounting, or cause-oriented LCAs – which are now known as attributional LCAs – and prospective, effect-oriented LCAs studying the effects of changes; i.e. consequential LCAs. Besides the attributional and consequential approaches, a third approach has been developed: the decisional approach (Frischknecht and Stucki 2010). This approach, which is illustrated by Guiton and Benetto (2013), allows calculating a new distribution of environmental impacts and benefits from the perspective of e.g. a company, based on contractual agreements. The decisional approach could be considered as the attributional approach for a hypothetical situation and is therefore not included as a separate approach in this thesis. These developments have a large influence on other aspects of the LCA methodology, such as the identification and application of a suitable allocation procedure in the inventory analysis (Tillman 2000; UNEP/SETAC Life Cycle Initiative 2011).

##### 4.1. Attributional LCA

Attributional LCA (a-LCA) is the approach that is most often applied, and it is often considered as the “traditional” approach for LCA. Several definitions could be applied to a-LCA. For example, Finnveden et al. (2009) state that *“attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems”*, which is similar to the understanding of Zamagni et al. (2008). In the Global Guidance Principles for LCA Databases (UNEP/SETAC Life Cycle Initiative 2011) we can find that the attributional approach is a *“system modeling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule”* and *“the attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle). In theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide”*. The ILCD

Handbook (European Commission 2010) states that attributional modeling comprises an *“LCI modeling frame that inventories the inputs and output flows of all processes of a system as they occur. Modeling process along an existing supply-chain is of this type”*. Curran & Mann (2001) state that *“attributional LCIs attempt to answer ‘how [are] things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?’”*, which has been interpreted by Pelletier & Tyedmers (2011) as *“An attributional LCA aims at isolating and describing the average environmental properties of a product or service life cycle”*. Heijungs defines the attribution problem as *“the question which environmental problems are to be attributed to which economic activities”*. He argues that one of the key questions in LCA is *“Which economic activity is responsible for which environmental problem?”* (Heijungs 1994). Ekvall, Tillman, & Molander (2005) consider that a retrospective – i.e. attributional – LCA is applied when it is understood that *“an environmentally good action reduces association with life cycles and subsystems with a high environmental impact”*. Also, Brandner (2016) states that *“attributional LCA is appropriate for assigning responsibility for a set of impacts [...]”*. According to Weidema, Ekvall, & Heijungs (2009), attributional LCA can be used to apply environmental taxation and to avoid blame for environmental impacts, which refer to liability for impacts. Responsibility and liability are both synonyms of *accountability* (Wordreference.com 2016). Attributional LCA is often referred to as an “accounting” approach (De Camillis et al 2013). Therefore, we could conclude that *attributional LCA aims to assess the accountability for impacts of the subject of the LCA*. The approach can be conceptually represented in the left picture of Figure 2-12. Data on actual suppliers or average market data are used in attributional LCA (UNEP/SETAC Life Cycle Initiative 2011).

#### 4.2. Consequential LCA

The consequential approach is applied to obtain information on the direct and indirect changes in environmental impacts due to a decision or a change in demand for a product. Only the processes affected by the change are considered, which are the marginal processes (Tillman 2000; Weidema 2003; European Commission 2010; UNEP/SETAC Life Cycle Initiative 2011). The definition of consequential LCA has been developed over the past years (Zamagni et al 2012). The UNEP/SETAC Life Cycle Initiative (2011) states that *“The consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product).”* Other definitions often emphasize the inclusion of market interactions in the consequential approach (Zamagni et al 2012). In consequential LCA, processes are included to the extent of their expected change caused by a demand (Weidema 2003; Weidema et al 2009; Zamagni et al 2012). De Camillis et al. (2013) state that in c-LCA the *“Baseline scenario is the World as it is, now or in the future, without any action. The question that the approach aims to answer is ‘what are the net impacts associated to a change (in a product system) relative to the baseline scenario, where that change does not take place?’”* In other words, consequential LCA aims to assess what impacts are caused by the subject of the LCA. This approach is depicted in the right picture of Figure 2-12.

#### 4.3. Area of application of the LCA approaches

Weidema et al. (2009) recommend to apply attributional LCA in a limited range of applications:

- Studies on a societal level, where it is aimed to identify for what impacts all human activities are responsible with the purpose to identify areas for improvement. Improvement options should subsequently be assessed by a consequential LCA
- Studies on environmental taxation that aims to focus on “who is to carry the burden”
- Studies that seek to avoid blame or praise for past good behavior, such as investments in sustainable production routes in the supply chain.

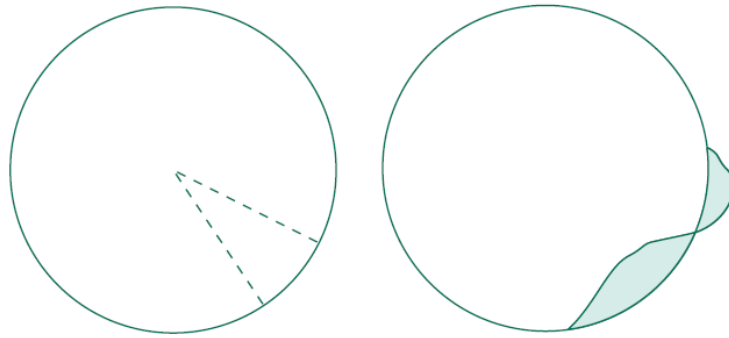


Figure 2-12 Conceptual difference between attributional (left) and consequential (right) approaches (Weidema 2003; UNEP/SETAC Life Cycle Initiative 2011)

They argue that, ultimately, LCA is used for decision-making and that consequential LCA is the most useful approach for this (Weidema et al 2009). Ekvall et al. (2005) argue that there is a risk that the environment is harmed by decisions based on attributional LCAs, due to the fact that consequences of individual actions are not assessed in this LCA approach. However, the inverse could also be the case: if decisions are only based on a consequential LCA, the assessment could motivate to make decisions that are suboptimal from a wider perspective (Ekvall et al 2005). The example is illustrated by Ekvall et al. (2005): a hotel installs a hydropower station to generate green electricity for the hotel. Any excess electricity is provided to the national grid. Here, the green electricity could substitute electricity from fossil sources. Any additional electricity consumption from this national grid results into an additional production from fossil resources – the marginal supplier. However, any consumption of electricity in the hotel reduces the amount of green electricity provided to the grid and consequently an additional production of fossil-based electricity. Therefore, the marginal supplier of electricity is the same for a user in the hotel as for the rest of the country. If the hotel aims to have more beneficial LCA results, it could be motivated to stop supplying electricity to the national grid. Any additional electricity consumption will be provided by the green source, although the surplus of green electricity that cannot be used at the venue is now lost. Additional information of an attributional LCA would indicate that, although electricity consumption at the venue could increase gray electricity production, the conference venue is not *accountable* for this electricity production. Therefore, we would argue that decision-making can be served by both an attributional and a consequential LCA. In Section 2.1 we identified three applications for decision-making: benchmarking, reducing global impacts and environmental portfolio management. From the discussion in this section we can conclude the following:

Attributional and consequential LCA can both support decision-making. Attributional LCA can be used for benchmarking and environmental portfolio management, and consequential LCA to assess global environmental impacts.

#### 4.4. Applicability of LCA approaches

Consequential LCAs are often considered more complex due to the inclusion of economic concepts such as marginal production costs, the elasticity of supply and demand, etc. (Zamagni et al 2012). This can have a negative effect on the ease of interpretation of the results. However, the inclusion of market mechanism adds to the realism of the calculated effects (Guinée 2002). Therefore, consequential LCA is a compromise between added realism and increased complexity. As long as all assumptions and choices are transparently communicated, the increased uncertainty does not have to be an impeding factor. It should be considered that many more attributional LCAs have been conducted than consequential LCAs, which has contributed to a broader understanding on attributional LCAs and the

availability of data that mostly support attributional studies. Consequential LCAs are not widely applied, and a consequential background database has only recently become available (Weidema et al., 2013). It is possible that the perception of increased complexity and uncertainty within consequential LCAs is related to the relative immaturity of this LCA approach.

## 5. Life Cycle Assessment supporting industrial goals

It is the objective of this thesis to identify a modeling approach that provides information that is relevant for companies. WRI and WBCSD (2011) compiled a list of business goals that represents the motivation for industries to establish a product GHG inventory (Figure 2-13). It is noteworthy that these goals refer to the accountability for environmental impacts of companies. This is related to risks associated with impactful products in a company's supply chain, costs within a life cycle related to impactful (ancillary) products – such as energy – and marketing of products that make consumers less responsible for environmental impacts. Most of these goals are well served by an attributional LCA. However, these goals do not necessarily support activities that reduce global environmental impacts. The consumption of “greener” products in the supply chain of a company could improve the company's environmental profile. It could also result in the fact that this green product is not available for another company anymore, which is now forced to use a more impactful product. In that case, the responsibility for impacts is redistributed among the companies while global impacts are not reduced.

<i>Business goal</i>	<i>Description</i>
<b>Climate change management</b>	<ul style="list-style-type: none"> <li>• Identify new market opportunities and regulatory incentives</li> <li>• Identify climate-related physical and regulatory risks in a product's life cycle</li> <li>• Assess risks from fluctuations in energy costs and material availability</li> </ul>
<b>Performance tracking</b>	<ul style="list-style-type: none"> <li>• Focus efforts on efficiency improvements and cost-saving opportunities through GHG reductions throughout a product's life cycle</li> <li>• Set product-related GHG reduction targets and develop strategies to achieve goals</li> <li>• Measure and report GHG performance over time</li> <li>• Track efficiency improvements throughout a product life cycle over time</li> </ul>
<b>Supplier and customer stewardship</b>	<ul style="list-style-type: none"> <li>• Partner with suppliers to achieve GHG reductions</li> <li>• Assess supplier performance for GHG aspects of green procurement efforts</li> <li>• Reduce GHG emissions and energy use, costs, and risks in the supply chain and avoid future costs related to energy and emissions</li> <li>• Launch a customer education campaign to encourage actions that reduce GHG emissions</li> </ul>
<b>Product differentiation</b>	<ul style="list-style-type: none"> <li>• Achieve competitive advantage by pursuing GHG reduction opportunities and cost savings to create a low-emitting product</li> <li>• Redesign a product to better respond to customer preferences</li> <li>• Strengthen brand image regarding GHG performance</li> <li>• Enhance employee retention and recruitment resulting from pride in product stewardship</li> <li>• Strengthen corporate reputation and accountability through public disclosure</li> </ul>

Figure 2-13 Business goals served by a product GHG inventory (WRI and WBCSD 2011)

### 5.1. Sustainability assessment

Environmental impacts are often considered as one of the three pillars of sustainable development, which covers three areas: environmental, economic and social issues (Heijungs et al 2010). Heijungs et al. (2010) state that “A thing is sustainable when it can be maintained in a specific state for an indefinite (or very long) time.” Companies could be motivated to do an LCA to assess their liability for impacts which could be translated into taxes or a bad image with their potential consumers, or to safeguard

the company's future supply chain. If actors in the supply chain are accountable for high impacts, their supply might not be guaranteed in the future considering the trend towards increased environmentally friendly production and measures that are taken against polluters. This has already been demonstrated by developments within the coal industry. Motivated by pressure from the society, investors are *en masse* "divesting" from coal-related projects, and several coal companies have filed for bankruptcy (The Guardian 2015; The New York Times 2015a; The New York Times 2015b). The public image had appeared to be a large drive behind these divestment decisions (De Correspondent 2017). Attributional LCA is suitable to quantify the degree in which a company can be associated with environmental impacts, hence to represent the environmental pillar of the sustainability of a company.

Environmental issues could influence the future operation of a company due to the risk of supply disruptions of crucial materials in the supply chain. However, supply disruptions can also be caused by other factors. This was demonstrated in 2011 by the REE supply crisis after China had decided to reduce the export of REEs. Many companies rely heavily on the supply of these elements, which resulted in the explosion of the market prices of all elements. This crisis has led the rest of the world to realize to what extent they are dependent on these materials, which motivated the European Commission to identify several materials as critical for the European economy.

## 5.2. Criticality assessment

Criticality assessment is a tool to systematically assess the risk due to the use of raw materials and their relative importance to an economy, either at micro-, meso- or macro-level (Sonnemann et al 2015). The European Commission executed a criticality assessment on several materials and identified 20 materials that are critical for the EU (European Commission 2014b). The method that they applied is based on the economic importance of the material for the European Union and the supply risk. The supply risk is dependent on the primary production from countries with poor governance, the availability of secondary supply from end-of-life products and the existence of substitutes.

However, the criticality assessment of the European Commission has not been connected to the Life Cycle Assessment framework. The integration of criticality in LCA has gained increased popularity in scientific literature since the publication of a methodological framework by Graedel et al. (2012). Schneider et al. (2013) argue that current consideration of resource depletion in LCA ignores the economic aspect of resource use and proposes a new impact category: the economic resource scarcity potential. However, Sonnemann et al. (2015) state that the economic resource scarcity, or supply risk, should not be part of an environmental LCA. Instead, supply risks provide us information on the economic criticality of resource use. This, together with the environmental criticality – which is calculated by environmental LCA – and social criticality, is part of a more holistic Life Cycle Sustainability Assessment. Sonnemann et al. (2015) provided a conceptual framework for the integration of criticality in a Life Cycle Sustainability Framework. In this framework, criticality applies to the environmental, economic and social aspects of resource use. Gemechu et al. (2016) developed this conceptual framework further by expressing the economic dimension by the indicators "geological supply risk", "geopolitical supply risk" and "vulnerability to supply restriction" (Figure 2-14). These issues were identified in Section 3.2 of this chapter as elements that motivate the recycling activities of critical raw materials. A Life Cycle Sustainability Assessment is an interesting tool to inform companies on the sustainability of their operation.

Attributional LCA can represent the environmental sustainability of a company with regard to the environmental impacts related to a product's value chain. A resource criticality assessment identifies the economic sustainability of resource use.



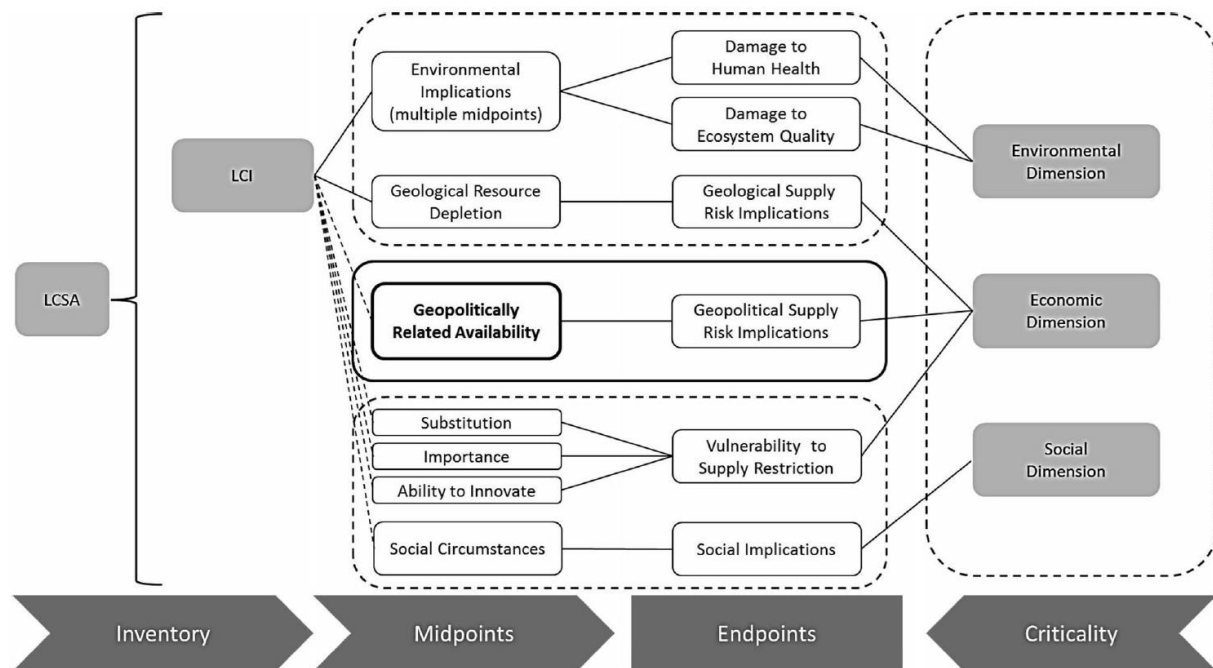


Figure 2-14 Integration of geopolitical-related supply risk and other criticality components within the life cycle sustainability assessment framework. The criticality assessment indicators are adapted from Graedel et al. (2012). LCI = life cycle inventory; LCSA = life cycle sustainability assessment (Gemachu et al 2016)

## 6. LCA goal-dependent allocation for recycling situations

As stated in Section 4, the LCA approach influences the way in which recycling is modeled in the LCA. It is often discussed whether the ISO standards refer to an attributional or consequential study. However, the standard states that no specific LCA goal is prescribed and that organizations have the flexibility to apply a methodology that suits the goal of their LCA study (ISO 2006b).

In a critical review, Zamagni et al. (2008) collected arguments of numerous critics indicating the limitations of the allocation hierarchy of the ISO standard. Different allocation approaches could be suitable for different LCA goals and decision contexts and the feasibility of the methods is not taken into account. Researchers have different interpretations of allocation hierarchy, regarding the most useful steps in the procedure, the applicability of system expansion and the identification of a relevant partitioning criterion (Zamagni et al 2008). There seems to exist consensus in the scientific domain that a multifunctional situation is solved by partitioning in attributional LCA and by substitution in consequential LCA (Pelletier, Ardente, Brandão, De Camillis, & Pennington, 2014; Tillman, 2000; UNEP/SETAC Life Cycle Initiative, 2011). However, difficulties in identifying the appropriate modeling approach and the avoided processes due to recycling cause that all possible combinations of modeling methods can be found in past LCA studies. In some studies, multifunctionality is not completely recognized, while in other studies incompatible methods are combined or choices of datasets are made inadequately and lacking justification (Laurent et al 2014). Sometimes the choice of attributional or consequential LCA, as well as the choice of partitioning based on physical or economic criteria is based on the preference of the LCA practitioner, instead of the LCA goal (Thomassen et al 2008; Pelletier et al 2014). Besides, the need is expressed to include the number of recycling loops in current methods (Finkbeiner 2013; Allacker et al 2014). Recently, Pelletier et al. (2014) underlined the need for a systematic and principled basis to solve multifunctionality in LCA. This is necessary to enhance the consistency, representativeness, and comparability of similar LCA studies (Pelletier et al 2014). However, Pelletier et al. focus on co-production and do not mention multifunctionality due to

recycling. Although co-production and recycling can be regarded as equivalent, recycling situations are not always treated as such. Therefore, it is useful to make this link explicit.

The lack of consensus in this field asks for a unifying theory to give more guidance on allocation in LCAs with different purposes (Curran 2007). In response to this need, the European Commission (2010) published the International Reference Life Cycle Data System (ILCD) Handbook. Several other official guidelines have been published as well, among which the Greenhouse Gas Protocol, BPX 30-323-0 (AFNOR) and PAS 2050. All these guidelines give slightly different recommendations to practice LCA and model recycling, which motivated the European Commission to increase methodological harmonization by publishing the Product Environmental Footprint (PEF) Guide (European Commission 2013), taking precedence over the ILCD Handbook. To enable reproducibility and comparability of LCAs, a single formula is proposed for all recycling situations (Pelletier et al 2013). Manfredi et al. argue that this contributes to high consistency of the method proposed in the PEF Guide (Manfredi et al 2015). However, this specific formula is mainly applicable to certain situations and materials, while for e.g. the metals sector the benefits of recycling are not well reflected (Eurofer et al 2013). Therefore, it is argued that the PEF formula does not enable comparability, but mainly introduces bias (Finkbeiner 2013). Allacker et al. (2014) recognize the fact that different approaches can be suitable for different goal definitions, although they argue that more consistency is required for the development of product policies regarding sustainable consumption and production. They assess several guidelines on their suitability for product policy-support. It is concluded that the PEF-Guide is, among other criteria, due to the 'one-formula-fits-all' approach better suitable for this purpose than other guidelines (Allacker et al 2014). Whether the possibility of the aforementioned bias could jeopardize the relevance of the LCA results and the value of the decisions based thereon is however not considered.

An overview of the lack of consensus on allocation procedures is given in Table 2-2. From Table 2-2 it appears that the link between the recommended or preferred allocation procedures from guidelines and industries and an attributional or consequential approach is not straightforward. Different documents often use different terminology for allocation procedures. Although it was suggested in the previous section that industrial goals might benefit from an attributional approach, the metals sector endorses an allocation procedure that could be considered as a 'consequential' method. A deeper understanding is required on what each allocation procedure represents, which LCA approach it serves and whether the LCA results obtained from the allocation procedure are relevant from an industrial perspective. This will be the focus of the following chapters.

Table 2-2 Impression on the lack of consensus with regard to allocation procedures for recycling situations

Stakeholder organization	Recommended allocation procedure
ISO 14044	Allocation hierarchy: 1. Subdivision 2. System expansion 3. Partitioning
Scientific domain	<ul style="list-style-type: none"> <li>• Partitioning (Attributional LCA)</li> <li>• Substitution (Consequential LCA)</li> </ul>
(Inter-)governmental guidelines	<ul style="list-style-type: none"> <li>• Substitution (PAS 2050, GHG Protocol)</li> <li>• Cut-off approach (PAS 2050, GHG Protocol)</li> <li>• 50/50 method (PEF Guide)</li> </ul>
Sectoral preferences or common application	<ul style="list-style-type: none"> <li>• Substitution (metals)<sup>a</sup></li> <li>• Cut-off approach (paper)<sup>b</sup></li> <li>• 50/50 method (plastics)<sup>c</sup></li> </ul>

<sup>a</sup>(Eurofer et al 2013)

<sup>b</sup>(The International EPD® System 2013a)

<sup>c</sup>(AFNOR 2011; Lehmann et al 2016)



## 7. Conclusions and hypotheses

The four phases of LCA – the goal and scope definition, the inventory analysis, the impact assessment and the interpretation phase – have been introduced in this chapter, jointly with the introduction to the case studies that are assessed in this thesis. The object of the LCA is the functional unit, which requires that the product system under study is monofunctional. However, most product systems, in reality, provide multiple functions, due to co-production, combined waste treatment or recycling. If the LCA aims to identify the impact of only one function, an allocation procedure must be applied. The introduction to the case studies – and more specifically to the case study on the recycling of rare earth elements of fluorescent lamps – illustrates that the multifunctionality issues of co-production, combined waste treatment, and recycling are closely connected. It has been suggested that the application of different allocation procedures to different multifunctionality situations is inconsistent. Whether it is possible to apply a single allocation procedure to situations of co-production, energy recovery and recycling is tested throughout this thesis by the following hypothesis:

Hypothesis 1: A single allocation procedure can be applied to recycled products, co-products and complex products that are involved with multiple multifunctionalities.

Some guidance is provided by ISO 14044 to apply allocation. However, ISO 14040 and 14044 do not refer to recent developments in the LCA domain, such as the existence of attributional and consequential LCA approaches. An LCA can be conducted to identify for what impacts a product is accountable – which requires an attributional approach – or to identify what impacts are caused by the additional demand for a product. The latter LCA goal is served by a consequential approach. The allocation hierarchy of ISO is not equally applicable in these different approaches. Several (governmental) guidelines have been developed to provide more concrete guidance on how to apply allocation. However, the guidelines provide convergent recommendations and encounter much criticism, for example from specific industrial sectors. This indicates that there is currently no consensus on how allocation should be applied, corresponding to the goal and scope of the respective LCA study. Instead, the allocation procedure that is applied is often influenced by the preferences of the LCA practitioner. The need for guidance for goal-dependent allocation is assessed by the second hypothesis:

Hypothesis 2: The allocation procedure is dependent on the goal and scope of the LCA.

Typical industrial goals suggest that industries are interested in the level of sustainability of their operations. The framework for Life Cycle Sustainability Assessment shows that an environmental LCA can provide information on the sustainability of a product or process with regard to potential risks related to environmental impacts. For this purpose, an attributional LCA can be useful, as this LCA approach shows what environmental impacts can be associated with a product or process. Attributional LCAs are furthermore more widely applied than consequential LCAs. However, the metals sector supports an allocation procedure that can be related to a consequential approach. This suggests that consequential LCAs can also provide information that is of interest to companies. This is tested by the third hypothesis:

Hypothesis 3: Both attributional and consequential LCA can serve objectives of industrial interest.

These hypotheses form the starting point of the research that is conducted in the subsequent chapters – building forth on the state of the art. The need for a consistent method for allocation that corresponds to the LCA purpose and the dissatisfaction with the PEF Guide by several stakeholders ask for further research into the obstacles for a consistent allocation approach that can be applied to all product categories without introducing bias. This is the main topic of the following chapters in this PhD

thesis. The names for the different allocation procedures in Table 2-2 are clarified in Chapter 3, and a more extensive overview of the recommendations of different guidelines is given in Chapter 4. In Chapter 4, it is furthermore assessed whether the recommendations of the guidelines can be supported by a scientific basis. Based on the findings of Chapters 3 and 4, consistent allocation procedures are further developed in Chapters 5 and 6. The application of these procedures is demonstrated in Chapter 7, and the relevance of the proposed allocation procedures for industrial sectors is discussed in Chapter 8. An answer to the research question of the thesis is given and the three hypotheses formulated in this chapter are tested in Chapter 9.



## Chapter 3: Development of a systematic framework based on the state of the art of allocation procedures for recycling situations in LCA

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### 1. Introduction

In the previous chapter, several allocation procedures for recycling situations were already mentioned: substitution, the cut-off approach, and the 50/50 method. These approaches and other methods are further clarified in this chapter. Allocation procedures are reviewed with the purpose to identify a systematic and consistent approach to apply allocation to recycling situations and ideally to multifunctionality problems in general, considering different LCA goals.

Although consistent guidance is sometimes interpreted as “*strict guidance allowing for limited flexibility*” (Manfredi et al 2015), we use the term consistency as being coherent, following logical reasoning. We address the recent understanding of the difference between attributional and consequential approaches by applying a strict separation between the two modeling methods, based on our interpretation on what these approaches imply and which is in line with (Tillman 2000; Weidema 2001; UNEP/SETAC Life Cycle Initiative 2011; De Camillis et al 2013; The International EPD® System 2013b). This interpretation has been introduced in Chapter 2. We also take reuse, data types and the number of recycling loops into account, as proposed by Allacker et al. (2014).

In the development of a consistent approach, it is important that unambiguous vocabulary is used. Therefore, first, the definitions and assumptions with regard to the key features of recycling in LCA as applied in this review and in the rest of the thesis are explained. Then, the most important allocation procedures are clarified and expressed in mathematical formulas. It is assessed for which allocation procedures multiple recycling loops are relevant. In conclusion, the state of the art is summarized in a framework, showing the relation between LCA goals and the allocation procedures based on their underlying objectives. The limitations of current allocation procedures are identified, which forms the basis for the next chapters. An earlier version of this chapter has been published in (Schrijvers et al 2016a).

### 2. Methods

This section first describes the assumptions and definitions that are used in this review and in the rest of the thesis. Furthermore, the review method is described.

#### 2.1. Combined production and joint production

In the discussions on multifunctionality situations in the LCA domain often the distinction between *combined production* and *joint production* is made. In the case of combined production, the production quantities of the co-products are independently variable. This is, for example, the case for the co-production of different boron products from one mineral resource (Azapagic and Clift 1999). In joint production, the relative output volume of the co-products is fixed (Frischknecht 2000; Weidema 2001). An example of joint production is the production of bitumen, gasoline, kerosene, gas oil and fuel oil from petroleum refinery (ISO 2012). Recycling is a typical example of joint production as well. The amount of recycled material that is available is inherently dependent on the amount of primary material that is produced. Therefore, the allocation procedures in this chapter and in the rest of the thesis will mainly refer to situations of joint production.

#### 2.2. Recycled content and end-of-life recycling rate

The rate of recycling can be quantified in various different ways. Terms that are often used are the recycled content (*RC*) and the end-of-life recycling rate (*RRE*). The recycled content is the input of

recycled material or co-product divided by a reference flow. In the report “Recycling rates of Metals” UNEP (2011) assimilates the recycled content to the *Recycling Input Rate*, and proposes a reference flow of ‘primary plus secondary material input’. This enables to assess how much primary production has been avoided by using secondary materials. This definition is also used in this thesis.

With regard to the end-of-life recycling rate of metals, UNEP (2011) distinguishes three levels: 1) the old scrap collection rate, which refers to the amount of metal that enters the recycling chain and is diverted from landfilling, 2) the recycling process efficiency rate – or recovery rate – of the recycling process of scraps into metals in their pure or alloy form, which is referred to as functional recycling and 3) the end-of-life recycling rate (EOL-RR) – i.e. the percentage of the material available after the use phase that is recycled or recovered. The EOL-RR also distinguishes functional recycling and non-functional recycling. Non-functional recycling appears when a metal is collected, but the metal remains an impurity in another material and the inherent function of the metal is not recovered.

The distinction of UNEP between functional and non-functional recycling is quite specific to for the metals sector. In this sector, functional recycling and non-functional recycling are sometimes assimilated to closed-loop and open-loop recycling or downcycling, respectively (e.g. (Dubreuil et al 2010; Koffler and Florin 2013)). These terms are further discussed in the next section. In other sectors, the link between non-functional recycling and open-loop recycling or downcycling is less obvious. For example, if a plastic is incinerated with the recovery of energy, a completely different ‘functional’ product (the recovered electricity) is created. The calculation of the recycling rate of energy in terms of quantities of plastics is less straightforward. Therefore, in this review the end-of-life recycling rate is defined as the amount of recycled material that is collected at the end of life divided by the available material after the use phase, corresponding to the old scrap collection rate of UNEP (2011) and the collection rate by Baumann & Tillman (2004). The rate is determined before losses due to transport to the recycling facility and further recycling procedures. The end-of-life recycling rate here also represents the amount of material that is sent to an energy recovery facility. Co-production is represented by the end-of-life recycling rate as the share of the intermediate flow that is valorized in order to produce the co-product. Furthermore, we apply an additional rate: the ‘conversion efficiency’. This rate corresponds to the recycling process efficiency rate of UNEP (2011), although in this thesis this rate is not limited to functional recycling. The conversion efficiency indicates the amount of the useful (co-)product that is produced per unit of material entering the valorization process.

### 2.3. Closed-loop recycling, open-loop recycling, and downcycling

If the recycled material that is made available at the end of life is used as a material input in the same product system, a closed material loop is formed and a closed-loop allocation procedure is applied. When the material is used in a different product system, e.g. because the properties of the material have changed, open-loop recycling is applied. An example for this is energy recovery after incineration of plastic waste where the electricity is used in another product system. We consider no relevant methodological difference between recycling and reuse, which can take place in a closed or open loop. Co-production could be regarded as open-loop recycling as well, due to the fact that a product is produced that is used in a different product system.

Downcycling can take place in closed-loop and open-loop recycling. Downcycling can appear in all material sectors. In the metals sector, it is often referred to as non-functional recycling that happens in an open loop (Dubreuil et al 2010; UNEP 2011; Koffler and Florin 2013). In other sectors, such as plastics and paper, downcycling is not necessarily “non-functional”. Recycling of polymers and paper does not always avoid primary materials in every application due to shorter polymer chains or fiber lengths, but in a mixture with primary material, the amount of the latter can be reduced. However,

generally a substitution of 100% is assumed because the substitution ratio is not always known (Laurent et al 2014). If downcycling is not acknowledged, it does not stimulate the production of high-quality secondary material. This could lead to a degradation of the recycled material pool (Koffler and Florin 2013). Downcycling can be incorporated by combining the end-of-life recycling rate with a quality-correction factor. Ideally, this correction factor represents to what extent the inherent properties of the material are lost, using the limiting factor as a quality parameter (European Commission 2013). If this cannot be easily determined, the market-price ratio of the recycled material and the substituted primary material could be used as an indicator (European Commission 2010; European Commission 2013). We interpret the quality-correction factor as the amount of primary material that can be replaced by recycled material (European Commission 2010). Finkbeiner (2013) argues that a quality-correction factor can be adjusted by the LCA practitioner to give desirable results. To avoid this, product-specific information on how to determine the quality of a material could be given in Product Category Rules. Koffler and Florin (2013) and Ligthart and Ansems (2012) stress the importance of finding the correct point of substitution, i.e. the material processing stage at which the market price is determined. This is also mentioned in the ILCD Handbook, where this point is referred to as the *true joint process*. To calculate the market-price based quality-correction factor the market-price ratio must be determinable and stable (Koffler and Florin 2013). In any case, a sensitivity analysis could be done on the quality-correction factor.

#### 2.4. Review approach

The starting point of the review is the categorization made by Tillman (2000), the UNEP/SETAC Life Cycle Initiative (2011) and Pelletier et al. (2014): (1) the impacts of a product system are *shared* with the recycled product, i.e. partitioning in attributional LCA, and (2) recycling *avoids* impacts elsewhere, which is the substitution method in – following the aforementioned categorization - consequential LCA. The description and modeling implications of attributional and consequential LCA that are provided in by the UNEP/SETAC Life Cycle Initiative are given in Table 3-1.

Based on scientific literature dedicated to allocation, as well as reasoning and argumentation used in official guidelines, the most relevant allocation procedures are identified. Allocation procedures are considered to be relevant if they have been referred to by recent official guidelines (e.g. the PEF Guide (European Commission 2013), the ILCD Handbook (European Commission 2010), PAS 2050 (BSI 2011a), BPX 30-323-0 (AFNOR 2011), and the Greenhouse Gas Protocol (WRI and WBCSD 2011)), or if they have been considered in recent comparative studies (e.g. (Thomassen et al 2008; Dubreuil et al 2010; Frischknecht 2010; Allacker et al 2014)). Comparisons with interpretations from older references are done as well (e.g. (Ekvall and Tillman 1997; Ekvall 2000; Baumann and Tillman 2004)), to show the development of the interpretation of the methods. The allocation procedures are expressed in mathematical formulas and schemes, which enables the identification of the core differences and the fundamental perspective of each allocation procedure. The formulas calculate the inventory ( $E_{tot}$ ) of one product life cycle in an open-loop recycling system, and they can consistently be applied to each subsequent life cycle without double counting or omission of processes, following the approach of Allacker et al. (2014) and the European Commission (2013). Although the total inventory of a product life cycle also includes, among others, the LCI of the use phase and distribution, these data do not require an allocation procedure and are, for clarity, omitted from the equations in Table 3-2. The formulas, which are mostly based on literature references, are modified to include all relevant factors, such as the material quality. The focus is put on the consistency between different multifunctionality problems: recycling, recovery, and co-production. In the development of a consistent approach, preference is given to allocation procedures that treat these situations equally. After identification of the most pertinent allocation procedures, other allocation procedures that are found in literature are

as much as possible categorized by the identified fundamental perspectives. In Chapter 2, different LCA application areas were identified: quantifying environmental impacts, identifying options for improvement and the three levels of decision-making: benchmarking and environmental portfolio management in attributional LCA and improving global impacts in consequential LCA. The applicability of the allocation procedures to these LCA application areas is assessed. Finally, a framework is developed that summarizes the results and allows for the identification of the most appropriate allocation procedure.

Table 3-1 Description and modeling implications of attributional and consequential LCA according to the UNEP/SETAC Life Cycle Initiative (2011)

	Attributional LCA	Consequential LCA
Description	<ul style="list-style-type: none"> <li>• <i>System modeling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule</i></li> </ul>	<ul style="list-style-type: none"> <li>• <i>System modeling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit</i></li> </ul>
LCA goal	<ul style="list-style-type: none"> <li>• <i>The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle)</i></li> </ul>	<ul style="list-style-type: none"> <li>• <i>The consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)</i></li> </ul>
Modeling implications	<ul style="list-style-type: none"> <li>• <i>In theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide</i></li> <li>• <i>The systems analysed ideally contain processes that are actually directly linked by (physical, energy, and service) flows to the unit process that supplies the functional unit or reference flow</i></li> <li>• <i>[This approach] uses data on actual suppliers or average data</i></li> </ul>	<ul style="list-style-type: none"> <li>• <i>In theory, the systems analysed in these LCAs are made up only of processes that are actually affected by the decision, that is, that change their output due to a signal they receive from a cause-and-effect chain whose origin is a particular decision</i></li> <li>• <i>[This approach] uses data on actual supplier as long as this supplier is not constrained (i.e., insofar as it can respond to an increase in demand with an equal increase in supply), otherwise uses data representing marginal technology (i.e., suppliers that will actually respond to a change in demand)</i></li> </ul>
Allocation procedure	<ul style="list-style-type: none"> <li>• <i>[This approach] commonly uses allocation<sup>a</sup> as a means to deal with multifunctional processes or systems</i></li> </ul>	<ul style="list-style-type: none"> <li>• <i>[This approach] uses a system expansion<sup>b</sup> approach to deal with multifunctional processes to expand the analysed system with additional processes</i></li> </ul>

<sup>a</sup> "Allocation" refers to partitioning in the report of the UNEP/SETAC Life Cycle Initiative (2011)

<sup>b</sup> "System expansion" refers to substitution in the report of the UNEP/SETAC Life Cycle Initiative (2011)

### 3. Results

In this section, an overview is given of the methods that are most often used to model recycling in LCA and the context in which they are applied. The allocation methods are represented by mathematical formulas in Table 3-2 (and Table 3-3)<sup>1</sup>. These formulas calculate the total inventory of the life cycle under study – excluding the use phase and distribution – per unit (e.g. mass) of the reference flow. Section 2 in Annex I shows how these formulas calculate the inventory for each life cycle in an open-loop recycling system as described by Ekvall and Tillman (1997). The formulas are schematically represented by Figure 3-1, Figure 3-3 to Figure 3-5 and Figure 3-7 to Figure 3-9. The figures represent an open-loop recycling system and show which processes are modeled by each life cycle. The focus is put on the 'current life cycle' (see Figure 3-1). Both primary and recycled material are modeled as inputs in the current life cycle. At the end-of-life, part of the material is transported to a recycling facility and recycled in a subsequent life cycle, the rest is treated as waste. To illustrate the connection between the life cycles, the distribution and use phases of the life cycle are included in the figures as well. However, these phases are not subject to allocation and are therefore not included in the equations of Table 3-2.



Figure 3-1 Legend corresponding to Figure 3-3 - Figure 3-9

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<sup>1</sup> The equations differ slightly from the equations in Schrijvers et al. (2016). A conversion factor is added in the consequential formulas and the explanation of some terms is adapted to be more in line with the equations in Chapters 5 and 6. The inventory of the recycling process is now expressed per unit of ingoing material. The conversion factor represents the quantity of useful product that is produced during the treatment of the ingoing (waste) flow.



Table 3-2 Mathematical expression of allocation procedures for recycling, co-production and energy recovery in LCA (references in text).  $E_{tot}$  refers to the total inventory that is attributed to one product life cycle in the (open-loop) recycling system – excluding the use phase and distribution.

LCA approach	Allocation method	Mathematical representation
Attributional LCA	Partitioning for open-loop recycling	1a) $E_{tot} = [E_v + E_d - RC * (E_v - E_{tot(n-1)} * F_{n-1}) - RRE * (E_d - E_{RRE})] * 1/(1 + RRE * C_{RRE} * F)$
	Partitioning for closed-loop recycling	1b) $E_{tot} = (E_v + E_d) * (1 - RRE * C_{RRE}) + E_{RRE} * RRE * C_{RRE}$
	Cut-off approach	2a) $E_{tot} = E_v + E_d - RC * (E_v - E_{RC2}) - RRE * (E_d - E_{RRE1})$ 2b) $E_{tot} = E_v + E_d - RC * E_v - RRE * (E_d - E_{RRE})$
	Consequential LCA	3a) $E_{tot} = E_v * \left(1 - RC \left(1 - \frac{Q_{RC}}{Q_v}\right)\right) + E_d - RRE * \left(C_{RRE} * \frac{Q_{RRE}}{Q_v} * E_v^* + E_d - E_{RRE}\right)$ 3b) $E_{tot} = E_v + E_d - RC * (E_v - E_{RC}) - (RRE - RC) * (E_v - E_{RC}) - RRE * (E_d - E_{RRE})$ 4) $E_{tot} = E_v + E_d - RC * \left(E_v + \frac{1}{C_{RC}} * (E_d^* - E_{RC})\right)$
	Waste mining method	5) $E_{tot} = E_v * \left(1 - RC \left(1 - \frac{Q_{RC}}{Q_v}\right)\right) + E_d - \frac{1}{2} RC * \left(E_v * \frac{Q_{RC}}{Q_v} + \frac{1}{C_{RC}} * (E_d^* - E_{RC})\right) - \frac{1}{2} RRE * \left(C_{RRE} * \frac{Q_{RRE}}{Q_v} * E_v^* + E_d - E_{RRE}\right)$
	50/50 method	

Table 3-3 Legend of terms of the equations in Table 3-2

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) (per unit of analysis) due to the material in the functional unit	LCI/unit of analysis
$E_{tot(n-1)}$	LCI (per unit of analysis) attributed to the functional unit of the primary product (or co-function) in the previous life cycle (or in the previous allocation occasion, e.g. if allocation first is applied to the co-products in a cradle-to-factory gate study, and subsequently to the primary and recycled co-product)	LCI/unit of analysis
$E_v$	LCI (per unit of analysis) due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI/unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
RC	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
RRE	End-of-life recycling rate ((1) recycled or recovered material collected at the end-of-life divided by the available material after the use phase, or (2) ratio of an intermediate flow that is valorized as a co-product)	$0 \leq \dots \leq 1$
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI/unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{RC}$	LCI due to the recycling or recovery processes that are related to the recycled content (including LCI of material losses during the recycling process). These processes can contain multiple sub-processes, such as transport to the recycling facility ( $E_{RC1}$ ) and the valorization activity ( $E_{RC2}$ )	LCI / unit of input material
$E_{RRE}$	LCI due to the recycling or recovery processes that are related to the end-of-life recycling rate (including LCI of material losses during transport). These processes can contain multiple sub-processes, such as transport to the recycling facility ( $E_{RRE1}$ ) and the valorization activity ( $E_{RRE2}$ )	LCI / unit of input material
$C_{RC}$	Conversion efficiency of the recycling process related to the recycled content	Unit of useful output / unit of input material
$C_{RRE}$	Conversion efficiency of the recycling process related to the end-of-life recycling rate	Unit of useful output / unit of input material
F	Relative economic value between the recycled or recovered material or co-product and the primary material (e.g. (€/MJ of electricity) / (€/kg of primary plastic)). If no economic allocation is applied: $F = 1$	Rate $\geq 0$
$F_{n-1}$	Relative economic value between the recycled/recovered material or co-product and the primary material that were produced in the previous life cycle. If no economic allocation was applied: $F = 1$	Rate $\geq 0$

Term	Explanation	Value
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$Q_{RRE}/Q_v^*$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material

### 3.1. Attributional LCA

In attributional LCA, the additional functions related to the co-products can be included in the functional unit by applying system expansion, the impacts can be partitioned over the co-products or the cut-off approach is applied. Multiple recycling loops can be relevant for system expansion and partitioning, which is further explained below.

#### 3.1.1. System expansion in attributional LCA

According to the ISO allocation hierarchy, subdivision or system expansion is the preferred method to solve a multifunctionality situation. Subdivision is not applicable in the case of joint production. In this thesis, we divide the act of system expansion – when the functional unit is increased to include the co-functions – and the act of substitution – i.e. the subsequent reduction of the functional unit by removing the co-functions – into two separate steps (Heijungs 2013). In the case of substitution, the avoided impacts of the conventional production of the co-products are subtracted from the life cycle under study. These steps are referred to as ‘system expansion’ and ‘system reduction’ in the ILCD Handbook (European Commission 2010). Although ISO 14041:1998 and ISO 14049 (2012) use the term ‘system expansion’ for both actions (Heijungs and Guinée 2007; Weidema 2014a), ISO 14044 only refers to the addition of functions – not the subtraction (Heijungs 2013). The UNEP/SETAC Life Cycle Initiative (2011) uses the term system expansion for both the addition and the subtraction of functions. For the sake of clarity and consistency, we apply a strict separation between the actions of system expansion and substitution.

System expansion can be applied in attributional LCA, while substitution is not always perceived as correct, as it takes place over time and therefore falls outside the scope of the snapshot that attributional LCAs provide (UNEP/SETAC Life Cycle Initiative 2011; De Camillis et al 2013; The International EPD® System 2013b). The impacts related to all global products do not add up to the worldwide impacts if substitution is applied (Heijungs 1997), which is the ideal application of attributional modeling according to its definition by the UNEP/SETAC Life Cycle Initiative (Table 3-1). Substitution is however widely applied in attributional LCAs. For example, waste incineration with energy recovery is often modeled as substitution of conventional electricity production. This could be condoned if a different definition for attributional LCA is applied than the definitions of UNEP/SETAC Life Cycle Initiative (2011) on which this review is based.

In our interpretation of system expansion, allocation can be avoided by extending the functional unit to include the additional treatment of wastes and production of co-products (Heijungs 2013). This is done by adding “the treatment of [ingoing waste]” and “the production of [outgoing co-product]” to the initial functional unit, as depicted in Figure 3-2. In the case of recycling, the new functional unit comprises both the function of the primary and the function of the secondary material. This is illustrated in ISO/TR 14049 (ISO 2012). System expansion can also be applied to materials that are recycled multiple times, which is explained in Section 3.1.3.

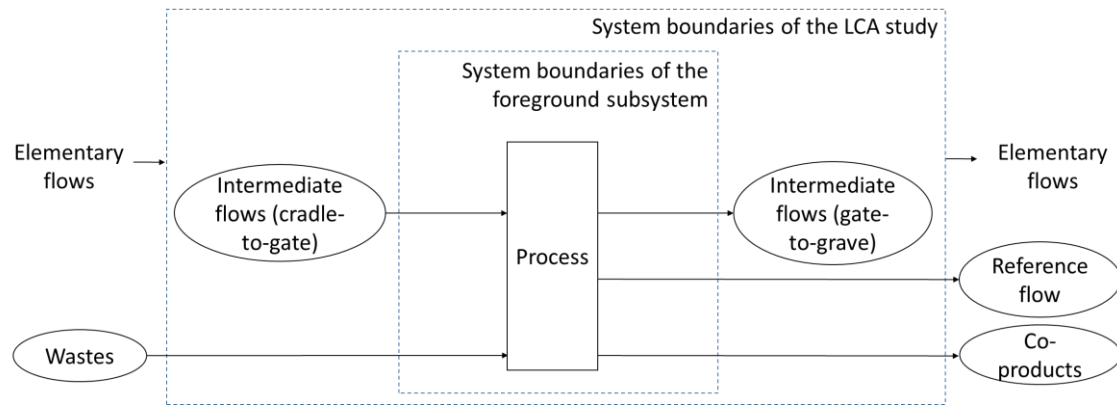


Figure 3-2 Application of “system expansion” by the inclusion of additional functions in the functional unit

System expansion is a good approach to ensure that all environmental burdens and credits are taken into account. It is important that recycling is modeled in a consistent way over the consecutive life cycles. If a product contains recycled material from a different product life cycle, i.e. open-loop recycling, it is tempting to consider the associated impacts to be zero, or only based on the recycling process. It is, however, possible that the practitioner of the LCA of the product that produces the recycled material already claimed a reduced impact, by attributing part of the impact of the primary product to the recycled product. Environmental impacts then get ‘lost’ between product life cycles. This is prevented by including the treatment of waste and the production of recycled materials in the functional unit.

In Chapter 2, the distinction was made between process-oriented and product-oriented LCAs. System expansion is only useful in process-oriented LCAs. In product-oriented LCAs, the aim is to provide background data for other LCA studies. Results from an LCA in which system expansion is applied cannot be used to represent only one product within the extended functional unit. System expansion can make the process-oriented LCA simpler when the purpose is to quantify the impacts of a process or to identify opportunities for improvement. If a comparison is done among alternative options in order to facilitate decision-making, for example for benchmarking, system expansion cannot always avoid applying an allocation procedure. The alternative product system that is used for comparison should provide the same functions as the system under study. Therefore, often it is necessary to find alternative production routes for the co-functions of the product system, which are added in the alternative product system. If those alternative production routes are multifunctional as well, the system can be further expanded or allocation should be applied.

In Chapter 2, environmental portfolio management was identified as another potential application of decision-making in an attributional LCA. In this type of LCA two product systems are compared that could both lead to impacts that are relevant for the concerned stakeholder. Full system expansion is not required, as not all functions might be relevant for the stakeholder. This type of assessment is only relevant in a process-oriented attributional LCA, where a stakeholder is interested in decreasing his own association with impacts and the number of functions is not a requirement. An example could be the case where a person tries to reduce his accountability for impacts by adopting more economical behavior, which could imply that the person has to pass on certain functions compared to his previous lifestyle.

System expansion can avoid partitioning in a process-oriented attributional LCA by adding “the treatment of [ingoing waste]” and “the production of [outgoing co-product]” to the initial functional unit.

### 3.1.2. Partitioning

If system expansion is applied, all functions of the product system are jointly accountable for all impacts caused by the product system. In a product-oriented attributional LCA, the aim is to identify the impacts for which one of these functions is accountable. Therefore, system expansion cannot be applied in an LCA that aims to provide data for further LCA studies. In that case, partitioning must be applied. In the partitioning approach, which is often simply called *allocation* (Heijungs and Guinée 2007), the inputs and outputs of the system are shared between the multiple functions according to a partitioning criterion. This criterion can be mass, energy content, market price etc. As a result, both the primary and the recycled or co-product carry a share of the impacts related to material extraction, material processing, recycling and waste treatment. Elaborate guidance on the identification of the process that requires partitioning (the true joint process), and choosing the appropriate partitioning criterion is given in the ILCD Handbook (European Commission 2010).

Originally, partitioning aimed to distribute the impacts of the primary production, the recycling processes and the final waste treatment over all the life cycles that use the material, as these processes are shared by several products in the open-loop recycling system (Ekvall and Tillman 1997; Baumann and Tillman 2004). This approach requires knowledge about all the subsequent life cycles. More recently, final waste treatment of the recycled material has not been considered as a process that requires partitioning in open-loop recycling (European Commission 2010; Weidema et al 2013). Weidema et al. (2013) consider recycled material as a co-product in the Overview and Methodology document of ecoinvent 3. In this document, waste treatment that takes place in the life cycle under study is partitioned between the co-products and the recycled materials that are produced by the same product system. This approach allows for an equal treatment of recycled material and co-products, which is pursued in this review. Assumptions about the final waste treatment process that is most likely to take place after several cycles of open-loop recycling are uncertain and require a level of speculation, which we consider outside the scope of an attributional LCA. Therefore, the partitioning approach as applied in ecoinvent 3 is considered to enable most consistency in the application of allocation in attributional LCA. This partitioning approach is further discussed in Chapter 5.

The partitioning method as adopted in this review is represented by Equation 1a in Table 3-2, Figure 3-3 and Figure 3-4. It should be noted that the LCA practitioner that focuses on the first life cycle of the system (i.e. the 'previous life cycle') partitions the inventory only between the first and the second life cycle (Figure 3-3). However, the inventory of the second – i.e. current – life cycle is partitioned between the current and the subsequent, i.e. third, life cycle. As the inventory of the second life cycle is partly established by processes that took place in the first life cycle, these processes are indirectly shared with the third life cycle as well (Figure 3-4). However, knowledge of the third life cycle is not necessary for the LCA practitioner that focuses on the first life cycle.

ISO 14044 prescribes a preference for partitioning reflecting physical relationships over economic partitioning. Physical relationships are relevant when the ratio between the co-products can be varied, i.e. in combined production (Azapagic and Clift 1999; ISO 2012). However, a physical relationship cannot always be identified, and economic values (or revenues) are often the drive behind certain activities (Guinée et al 2004), which makes market data relevant for environmental impacts. This is further reviewed and explained by among others (Ardente and Cellura 2012; Klöpffer and Grahl 2014; Pelletier et al 2014). Pelletier et al. (2014) have identified that physical partitioning often is applied to keep the natural science basis and physical realism of the LCA study intact. However, Weidema and Schmidt (2010) show that mass and energy balances do not stay intact if partitioning is applied. Economic partitioning is applied by practitioners who aim for a 'fair' distribution of impacts, following socioeconomic causality and incentivizing certain behaviors (Pelletier et al 2014). Similar to the choice

between attributional and consequential LCA, Pelletier et al. suggest choosing between a physical or socioeconomic rationale depending on the LCA goal. The choice for a partitioning criterion is further discussed in Chapter 5.

Another approach to partitioning is to estimate the share of impacts that is attributed to the co-product, using the conventional production process for this co-product as a proxy (De Camillis et al 2013; Guiton and Benetto 2013; Pelletier et al 2014). Majeau-Bettez et al. (2014) refer to this approach as ‘alternate activity allocation’, which corresponds to the ‘commodity-technology construct’ in input-output analysis. For each co-product, a single (monofunctional) alternative primary production route must be identified (Majeau-Bettez et al 2014). This co-product will always carry the impacts associated with its alternative primary production process. The remaining impacts of the product system under study – which can be negative – are subsequently allocated to the functional unit. Although a different rationale is applied, the results are similar to applying substitution. However, in the commodity-technology construct, the alternative production route could be identified based on “technological similarity” (Majeau-Bettez et al 2014). This is not necessarily the marginal process, which would have been chosen in the case of substitution. If multiple alternative production systems could be used as a proxy, the results might be poorly representative of the actual situation (Heijungs and Guinée 2007; Pelletier et al 2014). It might not always be possible to identify alternative processes that provide the same product (Pelletier et al 2014). Besides, we follow the interpretation of attributional LCA of the UNEP/SETAC Life Cycle Initiative, who state that *“The systems analysed ideally contain processes that are actually directly linked by (physical, energy, and service) flows to the unit process that supplies the functional unit or reference flow”* (see Table 3-1). As the alternative production route for the co-product is not directly linked to the functional unit, this partitioning perspective is not further considered in the systematic and consistent approach to allocation.

Critics of the partitioning method argue that the partitioning criterion is arbitrary or subjective, which can influence the LCA results (Heijungs and Guinée 2007; De Camillis et al 2013). However, Heijungs and Guinée (2007) argue that the partitioning method does not pretend to represent facts because it is an artificial solution to an artificial problem, i.e. solving multifunctionality.

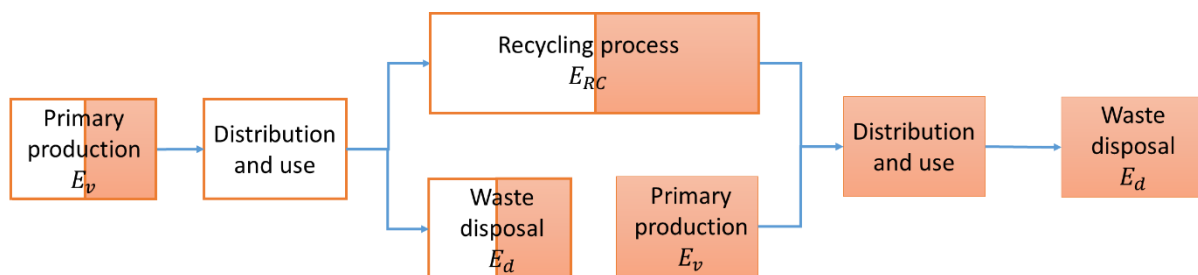


Figure 3-3 Schematic representation of partitioning between the first and the second life cycle in an open-loop recycling system.

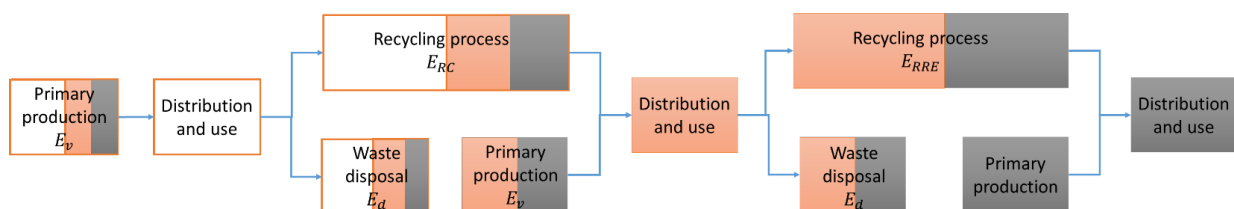


Figure 3-4 Schematic representation of partitioning between the second and the third life cycle in an open-loop recycling system. Impacts are shared between the first user and the second user of a material and can, therefore, propagate into subsequent life cycles

### 3.1.3. Multiple recycling loops in attributional LCA

Some products are suitable to be reused or recycled over and over again. This is, for example, the case for metals, solvents, and glass. Allocation can be quite straightforward if the material is used in a genuinely closed loop (Vigon et al 1993). In closed-loop recycling, there are no interactions with other product systems and allocation is not needed (Guinée et al 2004). Baumann and Tillman (2004) show the relationship between the number of life cycles (i.e. trip number) and the average end-of-life recycling rate per life cycle (adapted to include losses during the recycling process):

$$E1. \quad N = 1/(1 - RRE * C_{RRE})$$

Where  $N$  is the total use that can be obtained by one unit of material. For example, 1 kilogram of metal that is recycled with an end-of-life recycling rate of 50% provides the equivalent utility of 2 kg of primary metal (calculated by  $1 + 0.5 + 0.25 + 0.0625 + \dots$ ) (see (European Commission 2010)). System expansion is applied by redefining the functional unit to include the total number of uses of the material. Other inputs and outputs must be adjusted to this new functional unit. The average inventory per life cycle can be calculated with Equation 1b in Table 3-2 (based on European Commission (2010)).

It can be more complex if the material is recycled via a product independent recycled material pool (see ISO 14049 (2012)). In this case, it could be difficult to determine how often the consumed recycled material has been recycled before and what burden it should carry. Equation 1a of Table 3-2 is then difficult to apply, as this equation refers back to the previous life cycle. Equation 1a of Table 3-2 can then be represented as follows:

$$E2. \quad E_{tot}(n) = b * (a - RC * E_v) * \frac{1 - (b * RC * F)^n}{1 - b * RC * F} + a * b^{n+1} * RC^n * F^n$$

- $a = E_v + (1 - RRE) * E_d + RRE * E_{RRE}$
- $b = \frac{1}{1 + RRE * C_{RRE} * F}$

Where  $n$  indicates the (estimated) number of previous life cycles – i.e.  $n = 0$  in the life cycle where the material is used for the first time. This equation can be applied under the conditions that (1) it can be assumed that the inventory related to the primary production process, the recycling process and waste treatment in the previous life cycles are identical to the inventory of these processes in the current life cycle, *and* (2) assumptions can be made regarding the average recycled content and end-of-life recycling rate in the previous life cycles (for example market averages). After a certain number of recycling loops  $E_{tot}$  converges to a value, which can be calculated by the following:

$$E3. \quad \lim_{n \rightarrow \infty} E_{tot}(n) = b * (a - RC * E_v) / (1 - b * RC * F)$$

The application of Equations E2 and E3 is demonstrated with a hypothetical example of the recycling of aluminum in Section 3 of Annex I. The inventory per life cycle after several recycling loops (Equation E3) corresponds to the inventory per life cycle in case of closed-loop recycling (Equation 1b) when  $RC = RRE * C_{RRE}$ . This means that the amount of recycled material that is used in the life cycle should be equal to the amount of useful recycled material produced at the end of life.

The partitioning approach can calculate the inventory of a product that has been recycled multiple times before, while differentiating between the recycled content and the end-of-life recycling rate.

Neugebauer and Finkbeiner (2012) propose the “multi-recycling approach” to calculate the average LCI for a material that can be recycled multiple times. For the case of steel, 6 life cycles are assumed,



based on the lifespan of steel and an approximated average lifetime of a steel product. The inventory of 1 ton of primary steel, its waste treatment and the recycling process for 5 tons of steel are divided by the number of life cycles. From Equation E1 it appears that 6 life cycles would give an  $RRE$  of 83,3%. Implementing this rate in Equation E3 (and assuming  $RC = RRE * C_{RRE}$ ) results in the same impact per life cycle as using the multi-recycling approach. This conclusion can also be made when the term  $RRE * C_{RRE}$  in Equation 1b is expressed as  $1-1/N$  (see Equation E1). However, an important difference between the multi-recycling approach and Equation E3 is that the first applies a material perspective, instead of a product perspective. This means that the material is followed over its whole life cycle in which it can serve multiple functions in various products. This approach is only applicable to recycling situations in which the inherent properties of the material are maintained. The multi-recycling approach is therefore not consistently applicable to all multifunctionality situations.

#### 3.1.4. Cut-off approach

The cut-off approach, or the ‘recycled content approach’, is applied when the second function of the recycled product is not included in the analysis and only the products and processes directly related to the functional unit are responsible for environmental burdens (Ekvall and Tillman 1997). Potential co-functions (due to recycling, energy recovery or the production of co-products) leave the system boundaries as ‘burden-free’ outputs. In this approach, the environmental impacts of extraction and processing of a product are attributed to the first life cycle, i.e. the life cycle where recycled material is produced. If a product is recycled at the end-of-life stage, no impacts for waste management are considered. The impacts of the recycling process are attributed to the second life cycle (Frischknecht 2010). The formula representing this approach (Equation 2a in Table 3-2) is based on BSI (2011a), ISO (2013), and Allacker et al. (2014). This formula is visualized in Figure 3-5.

The cut-off method corresponds to the “polluter pays” method as described in the General programme instructions for the International EPD system (The International EPD® System 2013b) and Modules A to C in the CEN standard EN 15804 (CEN 2012). ISO/TS 14067 refers to this approach as ‘process subdivision’ (ISO 2013), which makes the method compatible with ISO 14044. Attention should be paid to the system boundaries: often the boundaries are set at the scrap yard or recycling facility (attributing transport to the first life cycle) (Vogtländer et al 2001; Peuportier et al 2011; WRI and WBCSD 2011; ISO 2013; The International EPD® System 2013b). Alternatively, the system boundaries are set at the process that generates a positive market value (Guinée et al 2004), or collection is attributed to the second life cycle (Frischknecht 2010). Note that the location of the system boundaries in Figure 3-5 is only one possible interpretation.

In the cut-off approach, recycling could lead to a lower impact of a product due to a reduced consumption of primary materials (for the consumed recycled material) or reduced waste management (for the produced recycled material). No consideration is given to the potential extra function that the recycled material could fulfill outside the current system boundaries, i.e. the motivation to use a certain material due to its recyclability is not reflected. We could, therefore, argue that the cut-off approach does not consider recycling to be a multifunctionality problem. If the recycled material has a market value of zero after the recycling process ( $E_{RC2}$ ), and if this defines the system boundaries (i.e. according to Equation 2b in Table 3-2), the cut-off approach corresponds to (economic) partitioning where 100% of the impacts are attributed to the functional unit of the previous life cycle and 0% to the recycled or co-product. This is also the result of Equation E2 where  $F = 0$ .

We consider the cut-off approach as a special case of partitioning where 100% of the impacts are attributed to the primary material and 0% to the recycled material.



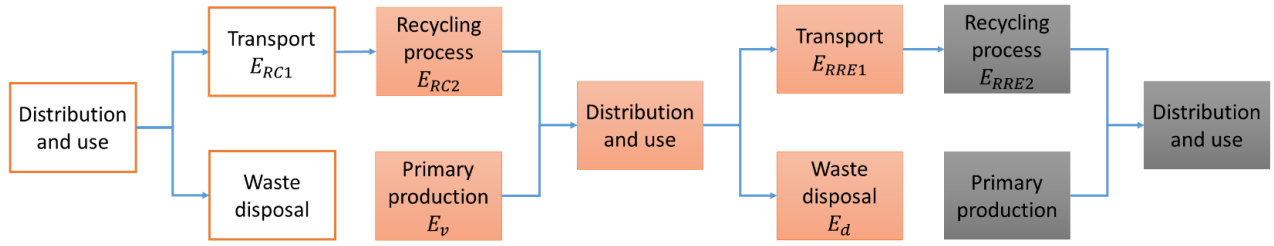


Figure 3-5 Schematic representation of the cut-off approach in an open-loop recycling system. In the cut-off approach, recycled products carry the impacts of the recycling process or are entirely burden-free

### 3.2. Consequential LCA

In consequential LCA, both direct and indirect consequences of a decision should be considered, as indirect consequences can sometimes offset the direct consequences or enhance the impact reduction (European Commission 2010). There are therefore ideally no system boundaries; all activities affected by the decision are included (De Camillis et al 2013). Whether or not indirect consequences are included in the analysis can lead to big differences in the outcome of the LCA (Merrild et al 2008). Impact partitioning is not possible, as co-functions and by-products are part of the consequences and therefore contribute to the impact of the functional unit (De Camillis et al 2013). To understand the modeling of recycling in consequential LCA, first, general assumptions in the consequential approach must be clarified.

#### 3.2.1. Supply constraints and demand constraints

Partial equilibrium models (PEM) or general equilibrium models (GEM) can be applied to calculate the effects of a changing demand in a consequential LCA, while interlinking several markets simultaneously (Zamagni et al 2012). The affected processes due to an additional supply of or demand for material can be determined by price elasticities. The price elasticity of demand is measured by the following:

$$E4. \quad \text{Price elasticity of demand} = \frac{\% \text{ change in quantity demanded}}{\% \text{ change in price}}$$

The price elasticity of supply is calculated by Equation E5:

$$E5. \quad \text{Price elasticity of supply} = \frac{\% \text{ change in quantity supplied}}{\% \text{ change in price}}$$

Ekvall (2000) introduced a market-based approach to allocation for open-loop recycling: additionally produced recycled materials can partly avoid primary materials, but might make recycling in other product systems less attractive due to a decrease in the price for this recycled material. Therefore, recycled materials might substitute recycled materials from other product systems, which now need to be treated as waste. Ekvall uses the price elasticities of supply and demand of the recycled material to quantify to what extent the consumption of primary material or waste treatment in other product systems is affected by the additional supply of or demand for recycled materials. The price elasticities should be determined on a case-by-case basis, as they depend, among others, on the time horizon and the geographical location. As it is not feasible to determine price elasticities for each single LCA, simplifications are often done (Ekvall and Weidema 2004):

1. The supply is fully elastic: the additional demand for a product leads to an additional supply of an equal amount
2. The supply is completely inelastic: the additional demand for a product does not lead to an additional supply, i.e. the supply is constrained

3. The demand is completely inelastic: the additional supply of a product is not absorbed by the market. Instead, the product is treated as waste. In other words: the demand for this product is constrained
4. The demand and supply are equally elastic, i.e. supply and demand for a product are equally constrained

The consequences of an additional supply of or demand for a material in different market situations are represented in Figure 3-6. These simplifications are not only relevant for recycled and co-produced materials, but for all materials in a consequential study. The supply of a product can be constrained if market imperfections exist. In that case, producers can influence the market prices, for example when they have a monopoly position (Weidema et al 2009). The supply of a product can also be constrained due to other reasons, among which the following (Weidema et al 1999; Weidema et al 2009):

- Regulatory constraints (e.g. emission, production or export quotas)
- Availability of capacity/raw materials
- Missing market for co-products
- If the product is a co-product itself

To further discuss supply constraints and demand constraints we need to distinguish between determining co-products and dependent co-products. The determining co-product is *“a joint product (a product from joint production) for which a change in demand will affect the production volume of the co-producing unit process”* (Weidema et al 2009). Even if the revenue of multiple co-products is required to cover the marginal operating costs, there is one product that puts an ultimate constraint on the production volume. The other co-products are identified as *“dependent co-products”*. Weidema et al. (2009) state that *“there will be a maximum of one determining co-product from each co-producing*

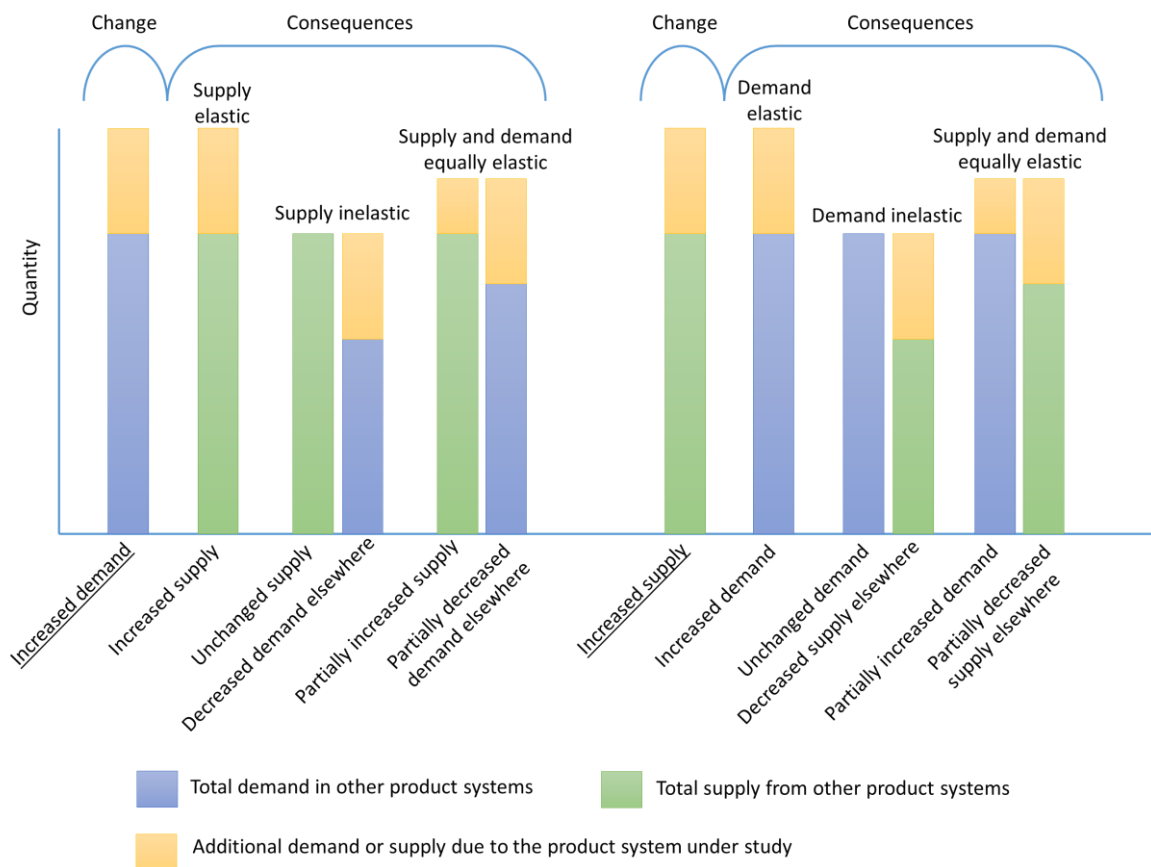


Figure 3-6 Consequences of a change in demand or supply of a product in different market situations

*unit process*”, unless if one of the co-products does not have an alternative production route (Weidema et al 2009). Further guidance in identifying the determining co-product is given by Weidema et al. (2009), Consequential-LCA (2015a), Consequential-LCA (2015b), and Consequential-LCA (2015c). Recycled products and co-products are typical dependent co-products of a primary product.

Generally, it is assumed in LCI, as well as in the ecoinvent 3 database, that the supply of a determining co-product is fully elastic: the additional demand for a product results in an additional supply (Weidema et al. 2013). This assumption is valid for competitive, unconstrained markets in the long term (Weidema et al. 2009). Effects on the long term are of interest in most consequential LCA studies, due to the fact that these effects contribute to decisions on capital investment (Weidema et al 2009; Weidema et al 2013). If there is a limited demand for a determining co-product, this will be solved in the long term by a reduced production volume of this product. Therefore, demand constraints are only relevant for dependent co-products, due to the fact that these co-products do not determine the production volume of the co-producing process. Dependent co-products have, by definition, also supply constraints: their supply is constrained by the demand for the determining co-product. In consequence, it should be identified whether supply constraints or demand constraints are dominant in the market of recycled materials and co-products.

From the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> simplification with regard to the price elasticities, three substitution methods can be derived to model recycling: the end-of-life recycling method, the waste mining method and the 50/50 method. We propose the ‘waste mining method’ as a new name for this method, as no clear denomination has been found in literature. First, it is discussed how modeling of substitution effects can be avoided by applying system expansion. Then, it is explained which substitution method corresponds to which market situation of Figure 3-6. This is summarized in Table 3-4.

### *3.2.2. System expansion in consequential LCA*

System expansion could be applied in both attributional and consequential LCA. Modeling the effects of the additional supply of or demand for recycled material can be avoided by including this production or consumption in the functional unit. However, system expansion is not always useful in a consequential LCA. As stated before, in this thesis, system expansion is applied by the inclusion of the additional functions in the functional unit, while in other LCA studies system expansion is often modeled as the avoided production of a material via an alternative production route. It has been demonstrated by other authors that system expansion and substitution are mathematically equivalent (European Commission 2010). As most LCAs will be used to compare two alternative options, modeling of indirect effects can be considered inevitable. Therefore, we considered that system expansion will only serve in a consequential LCA to demonstrate the sensitivity of the results by the inclusion of indirect effects. Increasing indirect environmental benefits or decreasing indirect environmental impacts can be an improvement option of a process, which is why this LCA purpose can benefit from the application of substitution.

### *3.2.3. The end-of-life recycling method*

The end-of-life recycling method has been described by, among others, Atherton (2007), Frischknecht (2010), Worldsteel Association (2011), WRI and WBCSD (2011), Leroy et al. (2012), Ligthart and Ansems (2012), and Eurofer et al. (2013). Benefits are attributed for producing recycled material, due to the fact that the production of primary material in the future is avoided. The consumed recycled material does not give environmental credits and carries the burdens of primary material. This is based on the assumption that, when recycled material is used as an input, this material cannot be used in another application and primary material must be used there (Ekvall 2000). This assumption is valid when all the recycled material is currently used and the supply of recycled material is constrained by the supply

of primary material (Weidema et al 2009) – i.e. supply is completely inelastic and demand is fully elastic (see Figure 3-6).

If the supply of a product is (partly) constrained, an increased demand for this product leads to a decreased demand in applications where it is easiest to opt for a different material if the product demanded becomes more expensive. This is the *marginal user* of the product. The marginal user of a product has the highest (absolute) price elasticity of demand. Frees (2008) argues that the supply of recycled aluminum should be considered inelastic: an increased demand does not lead to an increased production, as this production is constrained by the production of primary aluminum. Therefore, an increased demand for recycled aluminum will lead to an increased price, which results in a decreased use by the marginal user. The marginal user will now substitute the recycled aluminum with another product, for example, primary aluminum. Therefore, the consequence of an increased demand for recycled aluminum is the increased production of primary aluminum. The cross-price elasticity of demand could indicate whether the demand for primary aluminum is indeed affected by a change in the price of recycled aluminum (Zamagni et al 2008). The end-of-life recycling method is supported by several actors in the metals sector (Atherton 2007; Eurofer et al 2013). This implies that not only for aluminum but also for iron, steel, copper, zinc, and other base metals – and other industries that endorsed the preference for the end-of-life recycling method – supply constraints are dominant over demand constraints.

The inventory of the functional unit can be calculated by the end-of-life recycling method according to Equation 3a in Table 3-2, based on BSI (2011a), European Commission (2013), Wolf and Chomkhamsri (2014), and Allacker et al. (2014). Note that the quality-correction factor for the recycled content is necessary to calculate the amount of primary material that would actually have been used without the use of recycled material. For example, if 100 kg of recycled material is used as material input, this does not necessarily mean that the increased consumption of primary material in other life cycles equals 100 kg as well. If 100 kg recycled material could replace 70 kg of primary material, the quality correction factor  $\frac{Q_{RC}}{Q_v}$  would be 0.7. The primary material consumption is now modeled for only 70 kg. The formula is represented by Figure 3-7. Extending the system boundaries would cancel out the negative term of “avoided primary production” by the primary production that is modeled in the subsequent life cycle. Therefore, double counting and omission of processes are avoided. The avoided primary material and the 100% primary material in the subsequent life cycle should refer to the same material (Wolf and Chomkhamsri 2014). For example, if primary plastic is replaced by recycled aluminum, both life cycles should refer to either (avoided) primary plastic or (avoided) primary aluminum.

This method is also known under the names *Avoided burdens* (Heijungs and Guinée 2007), *Recyclability substitution* (European Commission 2010) or *Closed-loop approximation* (BSI 2011a). In the standard EN 15804 (CEN 2012) the life cycle is divided into Modules A to D. In Module A to C the cut-off approach is applied. However, Equation 2a is transformed into Equation 3b by including Module D. Module D assigns credits for the *net* production of recycled material (Peuportier et al 2011), which is calculated by subtracting the recycled content from the end-of-life recycling rate. This number can, therefore, be negative. When  $E_v$  and  $E_v^*$  are equivalent and the conversion factor and the quality-correction factor are 1, rearranging the terms leads to Equation 3a, i.e. the end-of-life recycling method.

In the end-of-life recycling method a material stewardship approach is applied (Atherton 2007): material is ‘borrowed’ if it can be recycled afterward. It does not matter if the material is conserved in nature or in the technosphere (Frischknecht 2010), the environmental impacts are minimized by the net conservation of material (PE Americas 2010). This method corresponds to the allocation

approaches that consider man-made materials as valuable resources; material lost as waste must be replaced (Ekvall and Tillman 1997; Baumann and Tillman 2004). Frischknecht (2010) considers this method as risk-seeking, as the environmental impacts are postponed to the future. However, this could depend on the representation of the results: If the actual primary production is fully modeled and the future avoided emissions are separately mentioned, the results might be easier to accept than if only the net results are shown and the impacts of the primary production are already reduced by the expected avoided future emissions.

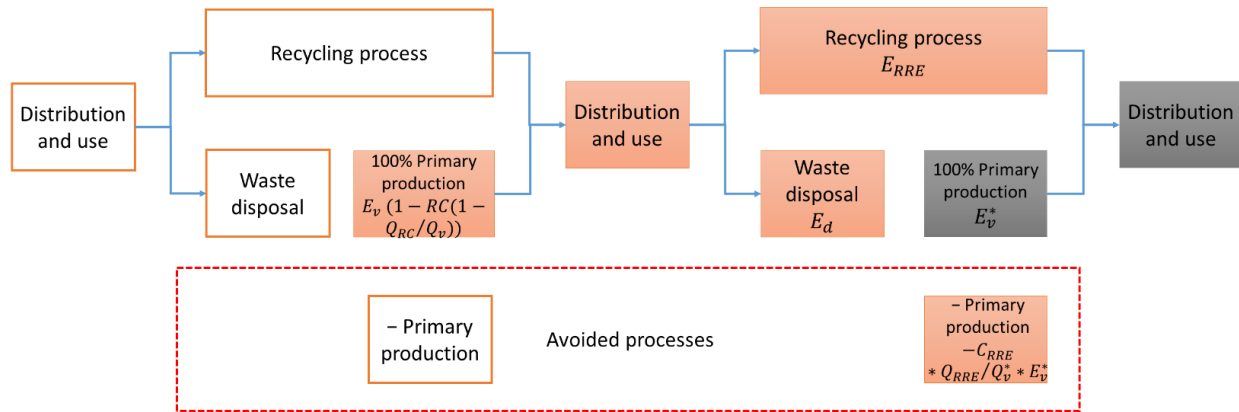


Figure 3-7 Schematic representation of the end-of-life recycling method in an open-loop recycling system. The production of recycled material at the end of life avoids the production of primary material in the next life cycle. The consumption of recycled material leads to an increased use of primary material in other product systems

### 3.2.4. The waste mining method

It is not always beneficial to produce recycled material, for example in a non-existent or shrinking market for this material (Weidema 2001; European Commission 2010). Increased production of recycled material could lead to decreased recycling in other life cycles, where the material is now treated as waste (Ekvall 2000). Also, the increased consumption of a co-product could avoid waste disposal if (part of) this product is normally treated as waste (Ekvall and Weidema 2004; Weidema et al 2009). This situation represents a fully inelastic demand for recycled material: the demand for this product is constrained (Figure 3-6). It was stated before that the supply of a recycled product is inherently constrained, as it is a dependent co-product. However, a fully inelastic demand is analog to a fully elastic supply – although not from primary production routes; any additionally demanded recycled material will lead to additional recycling and avoided waste treatment.

If the demand for a recycled material is constrained, the net *consumption* of recycled material should be promoted and credited for, which is done by the ‘waste mining method’. This method has been described in the ILCD Handbook, by Weidema (2001), Weidema et al. (2009) and NCASI (2012), but it has not been picked up by other guidelines. There is no clear definition for this method in literature yet. The direct opposite of the end-of-life recycling method is often considered to be the cut-off method (also referred to as ‘the recycled content method’ or ‘the 100-0 method’ (BSI 2011a)). Therefore, to avoid confusion, we propose ‘the waste mining method’ as a new definition.

The method can be represented by Equation 4 in Table 3-2 (based on the 50/50 method from the PEF Guide (European Commission 2013)) and the scheme in Figure 3-8. In the waste mining method, recycling leads to credits outside the product system by avoided waste management in the previous life cycle. The recycled material that is used as an input in the life cycle carries the burden of the recycling process. Impacts related to waste treatment in the previous life cycle are subtracted from the system. No environmental benefits are given for the production of recycled material. Instead, waste treatment is modeled as if the end-of-life recycling rate were zero. The results of the method

correspond to the approach that considers final waste treatment as a consequence of primary material extraction (Östermark and Rydberg 1995; Ekvall and Tillman 1997).

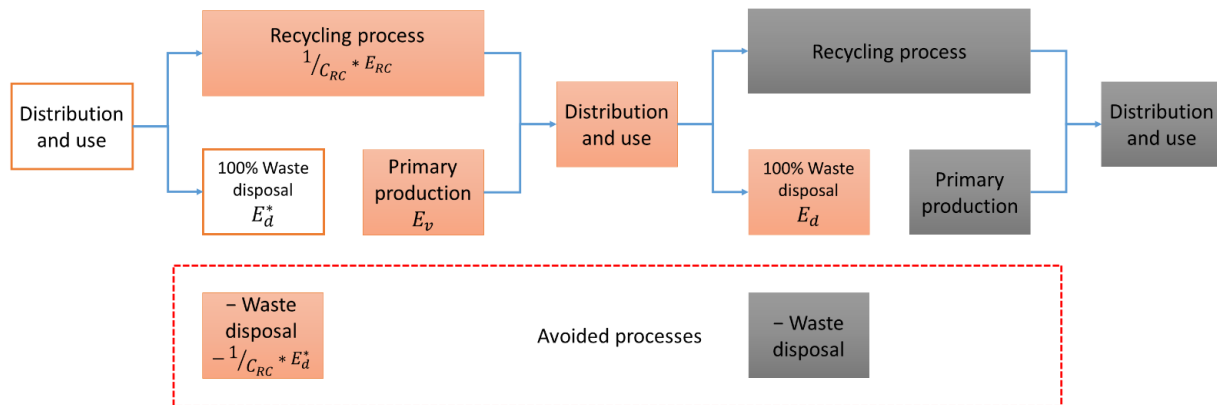


Figure 3-8 Schematic representation of the waste mining method in an open-loop recycling system. The additional demand for recycled materials leads to increased recycling and avoids that this material is treated as waste. The additional supply of recycled material does not lead to increased recycling, but to increased waste treatment in other product systems

### 3.2.5. The 50/50 method

Where recycling avoids either the production of primary material in the next life cycle (Equation 3a) or waste management in the previous life cycle (Equation 4), in the 50/50 approach the credits and burdens due to recycling are shared with both the previous and the subsequent life cycle. This results in Equation 5 in Table 3-2 and Figure 3-9, based on AFNOR (2011), Peuportier et al. (2011), and the European Commission (2013). This method could be applied as a compromise when it is not known whether the use or the production of recycled material should be promoted (Worldsteel Association 2011).

Originally the 50/50 method was proposed to share the impacts of primary production and final waste treatment between the first and the last life cycle of the material. The recycling process was shared 50/50 between the producer and the consumer of the recycled material (Ekvall and Tillman 1997; Baumann and Tillman 2004). Ekvall (2000) proposes the 50/50 method as a simplified consequential approach supported by the assumption that the price elasticity of supply equals the price elasticity of demand (Ekvall 2000), as represented in Figure 3-6.

Frees (2008) argues that the 50/50 method is not representative for recycled aluminum: the 50/50 method would assume environmental benefits due to the consumption of recycled material, while in this case, these benefits do not take place. Guinée (2002) considers the 50/50 method as a last-resort “quick-and-dirty” allocation method. AFNOR (2011) recommends using the 50/50 method for materials for which there is a lack of supply or demand, e.g. plastics. The 50/50 method is proposed as a mandatory formula by the PEF Guide (European Commission 2013), to be used for all material types. The differentiation of material markets by AFNOR was perceived “too complex to be directly used” (Galatola and Pant 2014).

Finkbeiner (2013) criticizes that the 50/50 method could never lead to a landfilling term of zero, even with 100% recycling. When the end-of-life recycling rate is 100%, it is not certain that the demand is high enough to consume this amount. This risk can be taken into account by sharing the credits with the subsequent life cycle. When all the recycled material is eventually consumed, all the avoided landfilling is credited for (50% in the current, and 50% in the subsequent life cycle). If recycled material is both consumed and produced in a products’ life cycle, the environmental impacts and benefits calculated by the 50/50 method are equal to the results produced by either the end-of-life recycling method or the waste mining method.

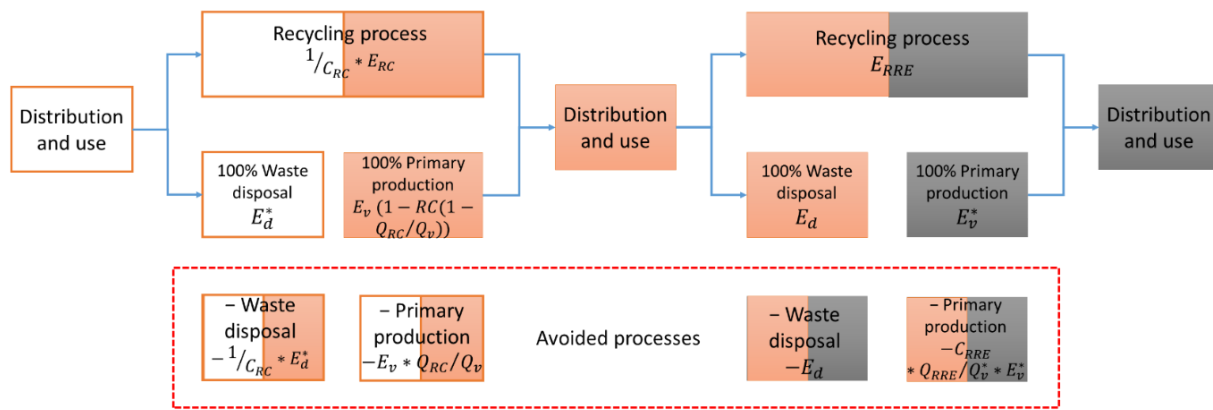


Figure 3-9 Schematic representation of the 50/50 method in an open-loop recycling system. The consumption of recycled material leads partially to increased recycling and avoided waste treatment and partially to a decreased use of recycled material – and increased use of primary material – elsewhere. The production of recycled material is modeled by the opposite effect

Table 3-4 Identification of the appropriate substitution method in the different market situations of Figure 3-6

	Supply constrained?	Demand constrained?	Substitution method
Determining co-product (The primary product)	Assumption: supply is unconstrained on the long term	Not relevant: a lacking demand will lead to a decreased supply in the long term	
Dependent co-product (The recycled product)	Yes: Supply is inelastic	No: Demand is elastic	End-of-life recycling method
	No: Supply is elastic	Yes: Demand is inelastic	Waste mining method
	Supply and demand are equally elastic		50/50 method

### 3.3. Systematic framework for goal-dependent allocation

Building forth on the frameworks as proposed by Tillman (2000) and Pelletier et al. (2014), we propose a systematic framework for consistent allocation in all multifunctionality situations in Figure 3-10. This figure shows how the methods that are expressed in mathematical formulas in Table 3-2 are positioned relative to different LCA approaches and to each other. The framework is applicable to co-production, recycling, and energy recovery. The LCA perspective indicates whether attributional or consequential LCA is applied. LCA studies with the aim to identify the accountability for impacts of a product system require attributional modeling, while LCA studies that aim to describe the effects of a change on global impacts require consequential modeling.

In an attributional LCA that focuses on a production, recycling or treatment process, system expansion can be applied by including all the co-functions in the functional unit. A comparison can be made with an average production route for benchmarking, or with a specific process for environmental portfolio management. In a product-oriented LCA, impacts are shared among the co-functions by partitioning. The cut-off approach is considered as a specific form of partitioning where 100% of the inventory is attributed to the life cycle under study and 0% to the co-function. In Table 3-2, two formulas were given for partitioning: one for open-loop recycling and one for closed-loop recycling. In closed-loop recycling, allocation is not necessary as the product system under study does not interact with other product systems (Guinée et al 2004). Formula 1b in Table 3-2 only aids to calculate the average inventory of the functional unit. Therefore, closed-loop recycling is not distinguished in the framework of Figure 3-10. Furthermore, the formulas for multiple recycling loops in attributional LCA (Equations



E2 and E3) are not specifically mentioned either, as these formulas are mathematically derived from Equation 1a – i.e. it is the same method.

In consequential LCA, the direct and indirect effects of multifunctional production and consumption are calculated by substitution. Modeling of substitution can be avoided by applying system expansion, although this is only considered relevant to indicate the influence of indirect effects on the results of the analysis. Three different substitution methods are identified: the end-of-life recycling method, the waste mining method and the 50/50 method. The latter calculates the average of the first two methods. The market situation of the recycled material indicates which substitution method is most appropriate. Downcycling can be considered by including a quality-correction factor, preferably based on relevant physical properties. If these are not determinable, the market-price ratio between the recycled and the primary material could be used as a proxy. In consequential LCA, marginal data are used to represent the substituted process.

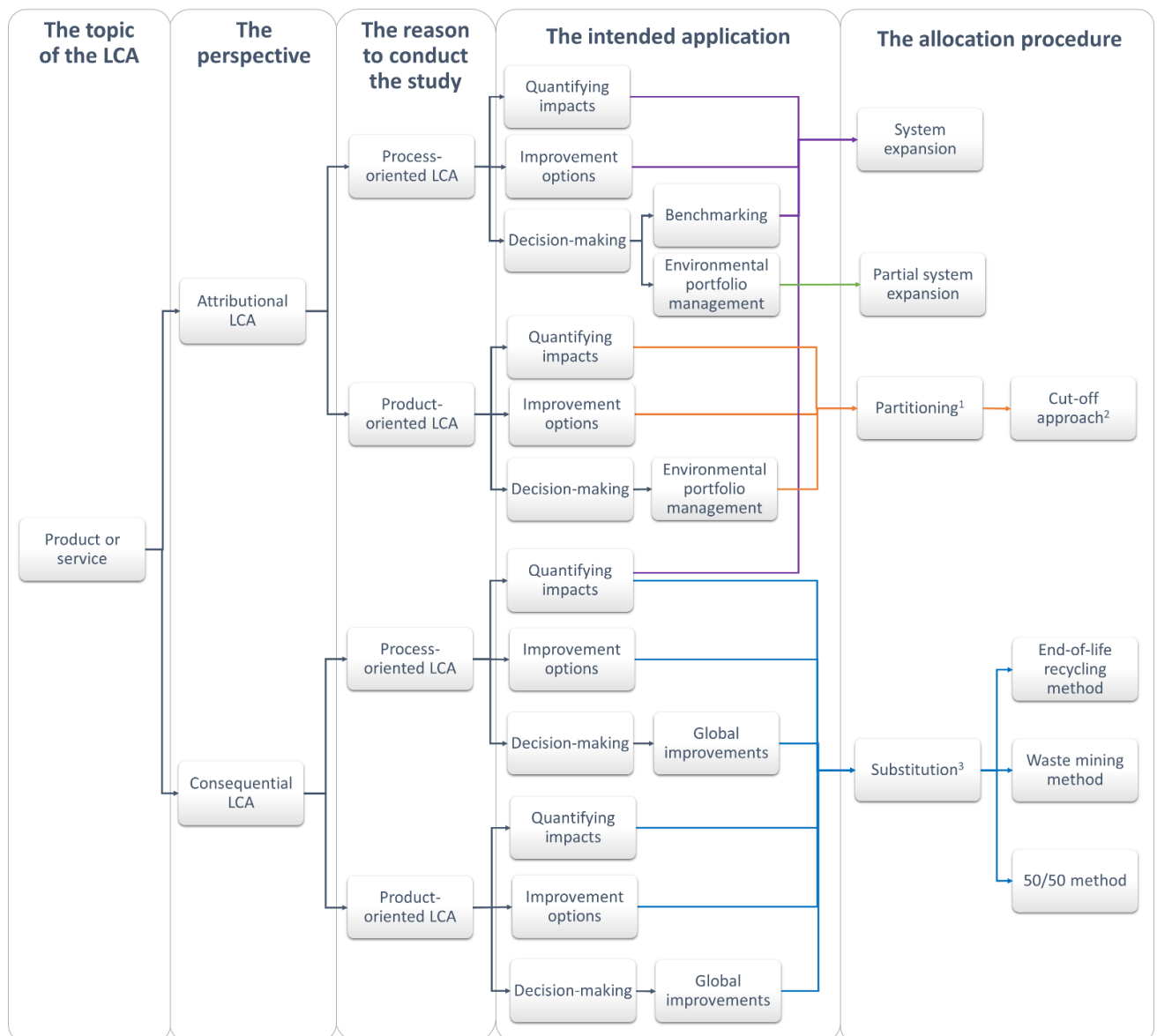


Figure 3-10 Systematic framework for consistent allocation in LCA. <sup>1</sup>No distinction is made between closed-loop and open-loop recycling such as in Table 3-2, due to the fact that closed-loop recycling does not require an allocation procedure. <sup>2</sup>The cut-off approach is considered as a specific case of partitioning where 100% of the impacts are attributed to the primary product. <sup>3</sup>The market situation of the material indicates which substitution method is applied



#### Archetypes of LCA goal and scope definitions

From Figure 3-10, it appears that a wide variety of LCAs can be conducted from one single topic. Choices in the goal and scope definition influence the type of question that is investigated by a typical LCA. These choices refer to the different elements of a goal definition as introduced in Chapter 2: the perspective of the LCA, the reason to conduct the study, the intended application and whether multifunctionalities must be solved or not – which are all influenced by the intended audience. From Figure 3-10, three key elements can be extracted that determine the methodology that is applied in an LCA: the perspective of the LCA, the reason to conduct the study and the functional unit. These elements reflect archetypes of LCA goal and scope definitions, as shown in Table 3-5.

Table 3-5 Building blocks of archetypes of LCA goal and scope definitions. The terms represented by  $\alpha$ ,  $\beta$ , and  $\gamma$  are used in the archetypal goal and scope definitions as defined in the box below

Item of the goal and scope definition	LCA approach	Building blocks of archetypal goal and scope definitions
The perspective of the LCA	Attributional LCA	$\alpha$ : Accountability for impacts
	Consequential LCA	$\alpha$ : Consequences on global impacts
The reason to conduct the study	Process-oriented LCA	$\beta$ : The production / valorization / treatment
	Product-oriented LCA	$\beta$ : The demand
The functional unit	Partitioning / Substitution	$\gamma$ : The topic of the LCA
	System expansion	$\gamma$ : The topic of the LCA and additional functions

The archetypes of LCA goal and scope definitions can now be expressed in the form of the following research questions:

Archetypal LCA goal and scope definitions	
-	<b>Quantifying environmental impacts:</b>
o	What is/are the $\alpha$ of $\beta$ of/for $\gamma$ ?
-	<b>Identifying opportunities for improvement:</b>
o	How can we decrease the impacts of $\beta$ of/for $\gamma$ , in order to decrease the $\alpha$ ?
-	<b>Decision-making:</b>
o	<i>Global impacts/Benchmarking:</i> Does $\beta$ of/for $\gamma$ have (a) lower $\alpha$ than its alternative?
o	<i>Environmental portfolio management:</i> Is [stakeholder] accountable for lower impacts due to the $\beta$ of/for $\gamma$ than in an alternative situation?

These research questions define the goal and scope on a level that is detailed enough to identify a suitable allocation procedure. Of course, it might be possible that other types of LCA exist as well. The approaches applied in this thesis could be extended to cover an even wider range of LCA goals.

## 4. Discussion

Due to the fact that allocation is a heavily debated topic, several elements of this review are subject to discussion. In this section, we evaluate the framework by criteria for allocation procedures of (Allacker et al 2014). Furthermore, we discuss the interpretation and distinction between attributional and

consequential LCA, mixing of allocation procedures and the use of price elasticities in consequential LCA.

#### 4.1. Evaluation of the framework

Allacker et al. (2014) formulated criteria that an allocation method should meet. We assess our proposed framework by these criteria as well. The framework is *comprehensive*, as the recycled content, the end-of-life recycling rate, virgin material, waste disposal as well as co-products and energy recovery are considered by the underlying methods. Both *open-loop and closed-loop recycling are accommodated*, where reuse can be considered to be analogous to recycling and energy recovery and co-production are regarded to be similar to open-loop recycling. The *recycled content and virgin material input are distinguished* when the use of recycled material actually leads to a reduced environmental impact. This condition enables “physical realism” because the use of recycled material does not always lead to a reduction of waste disposal or avoided primary material (e.g. when all recycled material is already used). Although the framework does not explicitly distinguish *recyclability and energy recovery rates*, both activities are covered by the framework and treated equally, leading to environmentally relevant information. *Credits for avoided material or energy* and other substitution effects are consequential by nature and are included accordingly. *Changes in inherent properties and downcycling* are taken into account by the quality-correction factor and are implicitly covered by the partitioning criterion in the open-loop recycling procedure in attributional modeling. Although a *physical correctness of flows at product level* causes double counting on a *system level*, life cycle assessments of similar goal definitions and LCA approaches can be done consecutively while maintaining physical correctness. Finally, *consistency for a wide range of application is enabled* by providing one framework for all LCA types while at the same time differentiating between LCA goals. LCAs with similar goal definitions, e.g. either benchmarking or decision making, are modeled according to the same approach and provide comparable information. Attributional and consequential LCAs are executed for different reasons and different types of information are generated. A comparison between these LCAs does not provide meaningful results. It can, therefore, be concluded that the framework of this review enables LCA modeling of recycling and co-product allocation in a systematic and consistent manner.

From the systematic framework, building blocks for archetypical LCA goal and scope definitions were distilled. The ILCD Handbook also introduced archetypical LCA goals. In this guidance document, Situations A, B, and C are introduced, that refer to different decision contexts (European Commission 2010). These different decision contexts are (A) micro-level decision support, (B) meso/macro-level decision support and – if the results do not have to support a decision – (C) accounting. The ILCD Handbook gives guidance in the application of an attributional or consequential approach and partitioning or substitution, although this guidance does not entirely correspond to the systematic framework of Figure 3-10. This is further reviewed in Chapter 4. Furthermore, the situations of the ILCD Handbook do not correspond to the archetypical goal and scope definitions that are identified in this chapter. For example, we consider that an accounting approach in which partitioning is applied can also support a decision – for example in the form of environmental portfolio management.

#### 4.2. Attributional and consequential LCA

Recently the discussion has intensified on whether attributional or consequential modeling is preferred for policy making (e.g. by Plevin et al. (2014b), Suh and Yang (2014), Dale and Kim (2014), Plevin et al. (2014a), Hertwich (2014), and Brandão et al. (2014). The fact that these two methods should not be combined has support within the European Commission (De Camillis et al 2013). Not everybody agrees with a strict separation between these LCA approaches (Suh and Yang 2014). However, the categorization of these terms contributes to the aspect of consistency in our reviewing

approach and at the same time addresses the potential of consequential modeling (Guiron and Benetto 2013), which is still not widely applied. Based on the definition of attributional LCA of the UNEP/SETAC Life Cycle Initiative (2011), as set out in Table 3-1, we interpreted “partitioning” as splitting the inventory across the co-products based on a common property of the co-products. Other interpretations are possible as well, e.g. the alternate activity allocation technique (Majeau-Bettez et al 2014). This partitioning technique might serve in an LCA based on a different definition for attributional LCA.

In this thesis, we applied the distinction between “accountability for impacts” and “consequences on global impacts”. There might appear to be no difference between these perspectives. One could argue that a product is accountable for the impacts that are caused by it. However, the nuance is very important for further modeling choices. A change in Product System A could influence choices that are made in Product System B. The indirect effects that take place due to these choices are a consequence of the activity in Product System A. However, Product System A is not responsible for the choices that are made in Product System B. Therefore, two different methodologies are required to identify the accountability for impacts of a product and the environmental impacts caused by a product.

The difference between attributional and consequential LCA can be visualized with the help of Figure 3-11. This figure shows the interactions on the market of a material between primary production, other applications that use the material, waste treatment, and recycling. Primary production routes provide a material to the market. This material is used in several different applications. At the end of life, this material is treated as waste, or the material is delivered back to the market due to a valorization activity. Co-products can also be brought to the material market via a valorization activity. Figure 3-12 shows what processes and actors are of interest when a recycled material is demanded from the market in an attributional LCA. The source of the material is traced by following the arrows that are directly connected to this material. The arrows show that the availability of the recycled material is dependent on the supply by other applications – potentially in multiple recycling loops, but in the end, the recycled material can be traced back to its primary source. In consequential LCA, it is identified which arrows – i.e. material flows – are affected by the demand for the recycled material (Figure 3-13). The increased demand for recycled material could lead to a decreased flow of recycled material to the general market of this material. This shortage can be supplemented by an additional production of the marginal supplier of the same material. Alternatively, the demand for recycled material can lead to a decreased flow of material to waste treatment. In that case, the supply of recycled material to the market is not affected, and waste treatment is decreased.

Figure 3-12 and Figure 3-13 give an indication of the type of data that must be known for an attributional and a consequential LCA on the demand for a product that is supplied by the market. It can be noted that an attributional LCA on a simple situation as described in Figure 3-11 requires data with regard to all processes and applications that contribute to the supply of the demanded material. In a consequential LCA, data collection is limited to the marginal supplier and the marginal user. This is the reason why Weidema et al. (1999) argue that average data are more uncertain than data based on marginal production. Large databases, such as ecoinvent, can provide an approximation of the inventory for an attributional LCA by including multiple production routes and considering the production volumes of these routes.

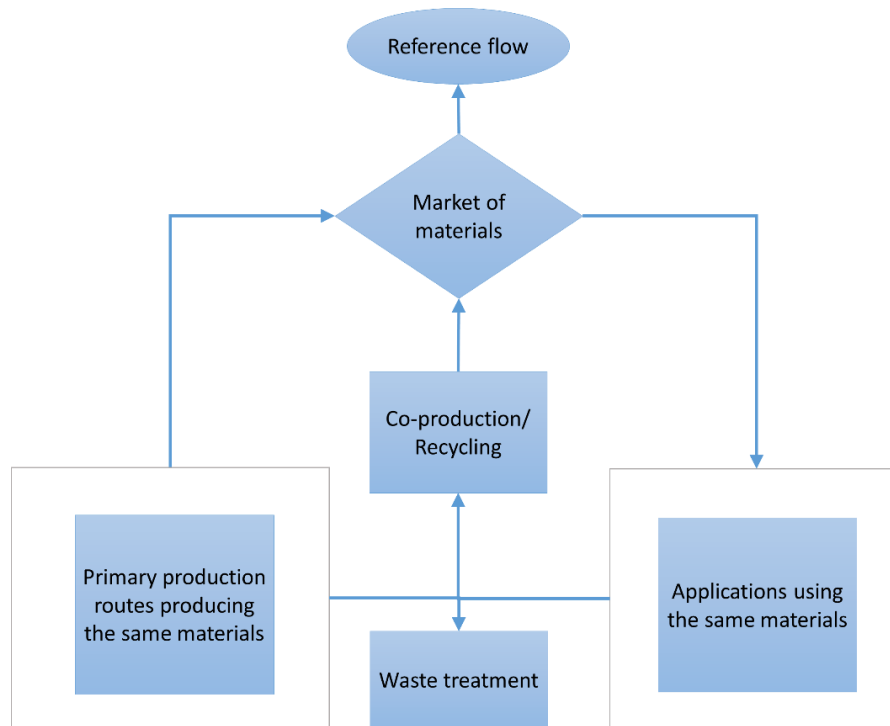


Figure 3-11 Typical connection between different actors and life cycle stages in the material market of the reference flow. Note that the arrows to waste treatment and recycling do not represent the end-of-life recycling rate of a material flow. Instead, the arrows represent potential directions of the flow

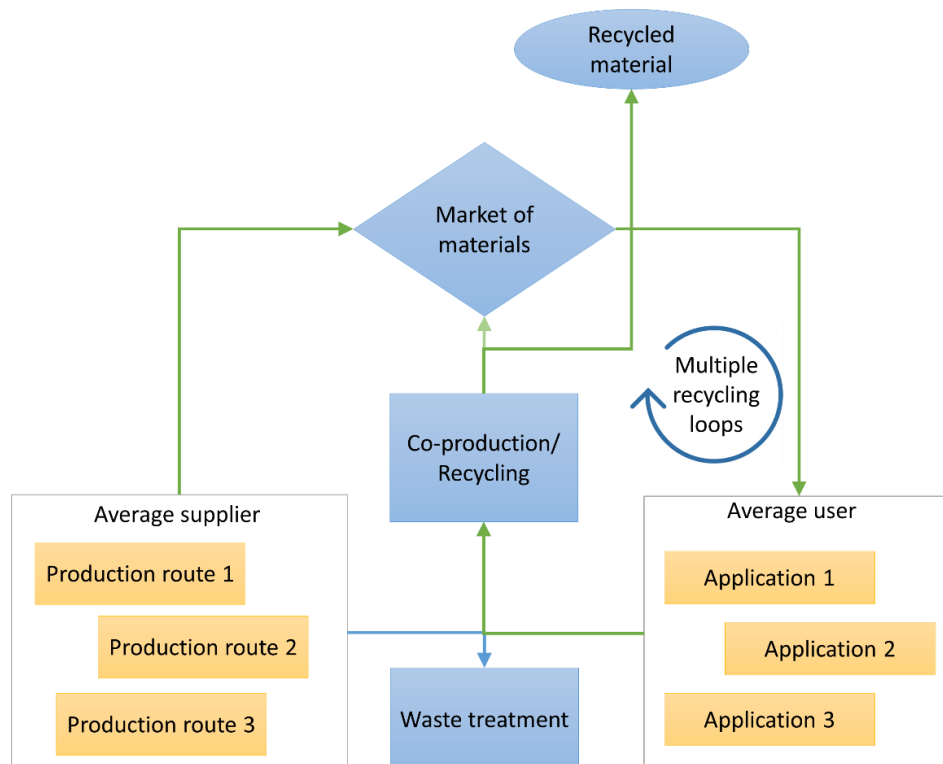


Figure 3-12 Processes of interest in an attributional LCA. It is identified on what production routes the reference flow is dependent. The reference flow is dependent on recycling from other applications, although in the end all material can be traced back to primary production routes

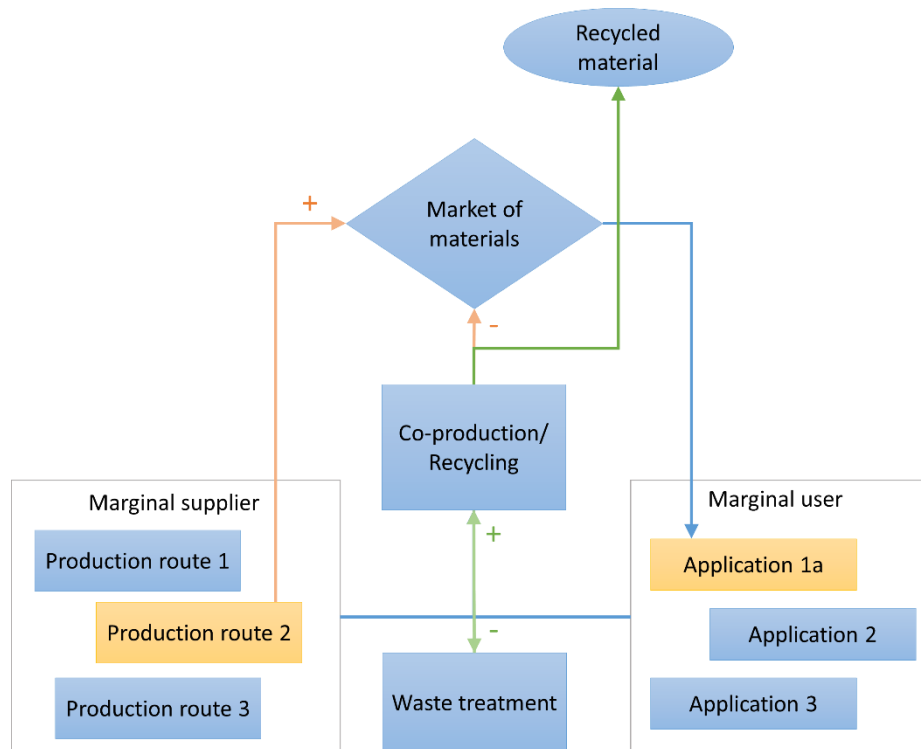


Figure 3-13 Processes of interest in a consequential LCA. It is identified which route is affected by the demand for the reference flow. This could be increased recycling and decreased waste treatment (in green), or a decreased supply of recycled material to the market, which leads to an increased production of primary material by the marginal supplier (in orange)

#### 4.3. Mixing of allocation procedures

In this review, we aimed to identify a consistent and systematic approach towards allocation in LCA, by considering the underlying objectives of each allocation procedure. These objectives are often disregarded, which results in mixing of attributional and consequential approaches. For example, in several studies, either the cut-off method or partitioning is compared with the end-of-life recycling method (Atherton 2007; Dubreuil et al 2010; Frischknecht 2010). Dubreuil et al. (2010) state that the cut-off method represents good environmental behavior in the case of a lacking market for the recycled material or avoiding (problematic) waste production. However, they do not consider that this market situation could also be represented by the waste mining method. Atherton (2007) argues that modeling according to the cut-off approach could lead to market distortions: if the recycled material is already fully used, an increase of the recycled content for a certain product could lead to a decreased use of recycled material elsewhere. The new application of the recycled material is not necessarily more environmentally beneficial, e.g. if transportation distances are increased (Atherton 2007). This is the reason why Atherton supports the end-of-life recycling method. The framework of Figure 3-10 shows that a comparison between the cut-off approach and the end-of-life recycling method should be avoided, as the methods serve different LCA goals.

The (indefinite) number of recycling loops can be taken into account when partitioning is applied, while no explicit notion of this is made in the end-of-life recycling method. However, consequential LCA assesses *effects*, instead of the historic pathway of a material that is assessed in an attributional LCA. This was illustrated in Figure 3-12 and Figure 3-13. Therefore, in a consequential LCA, environmental impacts or benefits are not “attached” to the recycled material, and do not propagate in future life cycles. Therefore, multiple recycling loops are not relevant in the end-of-life recycling method. This is also shown by Geyer et al. (2015). In fact, the partitioning method for open-loop recycling with no change in inherent properties after an indefinite number of recycling loops and the end-of-life recycling

method give the same results in two situations (in both cases only when  $Q_{RC}/Q_v = Q_{RRE}/Q_v^* = 1$  and  $E_v = E_v^*$ ):

$$E6. \quad RC = RRE * C_{RRE}$$

$$E7. \quad RRE = 1/(1 + (E_v - E_{RRE})/E_d)$$

For Equation E7 also the following should be valid:  $C_{RRE} = F = 1$ . More generally, from the mathematical comparison of the equations in Table 3-2 we can conclude that all methods described in this paper lead to the same results in the scenario of closed-loop recycling where the recycled content is equal to the end-of-life recycling rate and no quality loss takes place. This confirms that closed-loop recycling is not a multifunctionality problem that requires allocation.

#### 4.4. The use of price elasticities in consequential LCA

The choice between the three substitution methods in consequential LCA is indirectly based on (simplifications with regard to) the price elasticities of supply and demand of recycled materials (Table 3-4). Ekvall & Weidema (2004) assume that recycled material only competes with virgin material or recycled material of the same type. Increased consumption of the recycled material then directly influences the consumption and production of the primary equivalent, or similar recycled material. However, this is not necessarily the case. An increased supply of recycled plastic might not substitute primary plastic, but might substitute a completely different material, for example, paperboard as packaging material. This could be quantified by cross-price elasticities (Zamagni et al 2012). This type of modeling is further developed by Zink et al. (2015). These authors quantify the displacement ratio of a primary material by a recycled material using partial equilibrium modeling. Furthermore, they provide a causal loop diagram that represents the market interactions related to displacement. Relevant parameters in their methodology are the price elasticity of supply and demand and cross-price elasticities of both the primary and the recycled material. The method calculates the displacement ratio of two materials that are considered to be substitutes. It appears that no displacement of primary material takes place when the supply of primary material is inelastic (i.e. fully constrained) or when the cross-price elasticity of primary demand for secondary material is zero, i.e. the materials are not good substitutes. The authors argue that the recycled material might not be considered a good substitute for primary materials due to technical constraints or quality requirements. Full displacement only takes place if buyers of primary materials are equally motivated to use recycled materials as vice versa (Zink et al 2015).

The application of PE and GEM and the use of price elasticities have limitations, which are already often discussed in the LCA domain. Kätelhön et al. (2016) state that PE and GEM are limited by econometric data, and that these data are often only generated on an aggregated sector basis. This does not provide the necessary level of detail that is often desired in LCAs. Furthermore, price elasticities are often valid for the short term (Ekvall and Weidema 2004; Zamagni et al 2008). The short-term market behavior might not reflect well the considerations related to long-term investment decisions (Weidema et al 2009). However, long-term price elasticities are more difficult to calculate (Zamagni et al 2008). Price elasticities are used to represent negative feedback mechanisms, however, positive feedback mechanisms exist as well. The increased use of a material can inspire other consumers to use this material as well, increasing the demand even further (Ekvall & Weidema, 2004). If supply and demand increase simultaneously, the empirically identified price elasticities do not predict the indirect effects in a representative manner.

The approach of Zink et al. (2015) is a very comprehensive approach to calculating the displacement rate of a specific material due to the additional supply of a recycled material. However, the approach does not give further guidance on how to identify (better) substitutes. If multiple products could be identified as potential substitutes, the method of Zink et al. should be repeated for different materials, while for all alternatives price elasticities of supply and demand as well as cross-price elasticities are required. Up to date values are not always available for each material or for the time horizon that is considered in the LCA. In the model of Zink et al., no guidance is given on how to identify the consequences of a partial displacement. This is modeled by additional or avoided waste treatment in the market-based approach of (Ekvall 2000). However, Johnson et al. (2013) criticize that this approach does not consider stockpiling.

The simplified assumptions on the elasticities of supply and demand can be reduced to the question whether supply constraints or demand constraints are dominant in the market of a material. The fact that the metals sector supports the end-of-life recycling method indicates that in this sector supply constraints are dominant. The 50/50 method was considered representative for the plastics sector. Plastics Recyclers Europe (2012) discuss that the plastics sector would indeed benefit from an increased recycled content as well as an increased end-of-life recycling rate, therefore both supply constraints and demand constraints are relevant. Due to the aforementioned limited availability of price elasticities, other indicators must be identified to determine the relevance of constraints of supply and demand in other material markets. However, recycled materials are not always traded on the market. Therefore, a method is needed that can also assess the consequences of the demand from or supply to another product system if the materials are directly traded between the actors in the recycling chain.

## 5. Conclusions

In the previous chapter, modeling of recycling in LCA was identified to be a problem of allocation. The current chapter aimed to identify a consistent allocation procedure to model recycling in diverging situations.

A state of the art of allocation procedures is provided that can be applied to various types of multifunctionality situations. The developments of attributional and consequential LCA in the scientific domain are taken into consideration and the allocation procedures are categorized accordingly. Each allocation procedure is captured in the form of a mathematical equation. This enables to identify the differences in the mechanisms of the procedures.

It is found that there is a relevant difference between process-oriented and product-oriented LCAs. A process-oriented LCA aims to assess the environmental performance of a process, while a product-oriented LCA aims to identify the environmental impact of one product. Data of the latter can be used as background data in further LCA studies. System expansion can avoid partitioning in a process-oriented attributional LCA by adding “the treatment of [ingoing waste]” and “the production of [outgoing co-product]” to the initial functional unit. System expansion can also avoid modeling the effects of recycling in a consequential LCA. However, these effects are often of interest due to the fact that indirect effects might offset direct impacts or benefits, which makes the usefulness of system expansion limited in a consequential LCA. While system expansion can be applied in attributional LCA, substitution is not always perceived as correct, as it takes place over time and therefore falls outside the scope of the snapshot that attributional LCAs provide.

In a product-oriented attributional LCA, allocation is applied by partitioning. From the partitioning formula, a new equation is derived to calculate the impact of a product that has been recycled multiple times before. This demonstrates that multiple recycling loops influence the impacts of a product in an

attributional LCA. The formula allows for a differentiation between the recycled content and the end-of-life recycling rate, which has not been considered in other methods that consider multiple loops. The cut-off approach is considered as a special case of partitioning where 100% of the impacts are attributed to the primary material and 0% to the recycled material.

In a consequential LCA, the effects of additional recycling are modeled by substitution. Three substitution methods are identified that model the effects of recycling:

- In end-of-life recycling method, the additional supply of a recycled material can avoid the production of a primary material in the next life cycle. The additional demand for recycled materials is modeled by the additional supply of primary materials.
- In the waste mining method, the additional demand for a recycled product leads to additional recycling and avoids that this product is treated as waste. The additional supply of recycled material is modeled by additional waste treatment.
- In the 50/50 method, the consumption of recycled material partly avoids waste treatment and partly leads to an increased production of primary material. The additional supply of recycled material partly avoids the production of primary material in the next life cycle and partly leads to additional waste treatment. The 50/50 method, therefore, models the average of the end-of-life recycling method and the waste mining method.

The choice between the three substitution methods is based on the market situation of the recycled materials:

- A completely inelastic supply of recycled materials asks for the end-of-life recycling method. This method could well reflect the market situation of several base metals.
- The waste mining method is used when the demand for recycled material is fully inelastic.
- The 50/50 method represents the situation in which supply and demand of the recycled product are equally elastic. This method is sometimes associated with the market situation of plastics.

A systematic framework is developed that summarizes the findings of this chapter and links the allocation procedures to an attributional or a consequential approach and a process-oriented or product-oriented perspective. Furthermore, it is considered in the framework that attributional and consequential LCA can serve different application areas: quantifying impacts, identifying opportunities for improvement and decision-making. From the framework, it appears that three elements of the LCA goal and scope definition directly influence the suitability of an allocation procedure:

The perspective of the LCA: what does the LCA calculate?

- The accountability for impacts
- The consequences on global impacts

The reason to conduct the study:

- Assess the environmental performance of a production, valorization or treatment process
- Identify the impacts related to the demand for a product

The functional unit

- One specific function is assessed
- Multiple functions are taken into consideration

From these elements, archetypes of LCA goal and scope definitions are formulated. The allocation procedures that are included in the systematic framework are applied to these archetypical LCA studies. On the other hand, the identification of relevant allocation procedures is limited by these archetypes of goal and scope.



## 6. Perspectives

A simplified version of the systematic framework developed in this chapter is compared to the recommended allocation procedures of guidance documents – including the ISO standards, the PEF Guide, PAS 2050 and the GHG Protocol – in Chapter 4. From the framework, it appears that, in an attributional LCA, a multifunctional situation is solved by partitioning. However, the framework does not give guidance in *how* to apply partitioning. This guidance is further developed in Chapter 5. Three substitution methods could be applied in a consequential LCA. The choice between these substitution methods is currently often based on (assumptions on) the elasticities of supply and demand of the recycled material. While actors in the base metals and plastics sectors have already indicated which substitution method is most suitable for these respective sectors, it is unclear how this preference can be translated to other product sectors. The limitations of price elasticities and the need for other indicators to represent constraints of supply or demand of materials – that are not necessarily traded on the market – were discussed in this chapter. Furthermore, it was argued that stockpiling is not considered in current substitution methods. These issues are addressed in Chapter 6.

Finally, the systematic framework is tested on the three different case studies that were introduced in Chapter 2. In each case study, both an attributional and a consequential approach are applied. A broad range of research questions is investigated, covering the archetypes of LCA goal and scope definitions that were introduced in this chapter. Different LCA purposes and process-oriented and product-oriented perspectives are applied. In Chapter 8 it is discussed which of the types of LCA goal and scope definitions are relevant for an industrial stakeholder.

## Chapter 4: Critical review of guidelines against a systematic framework for allocation

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### 1. Introduction

In Chapter 3, a range of allocation procedures was identified that could make a multifunctional product system in which recycling takes place monofunctional. The allocation procedures that are most often used are partitioning, the cut-off approach, the end-of-life recycling method, and the 50/50 method. Furthermore, the waste mining method has been identified as the counterpart of the end-of-life recycling method. The end-of-life recycling method is often used as a synonym for “system expansion”. However, in Chapter 3, system expansion is not referred to as a substitution method. Instead, system expansion can be applied to include the functions provided by the additionally produced materials in the functional unit.

These allocation procedures were categorized in a systematic framework for consistent allocation in LCA in Chapter 3. System expansion, partitioning, and the cut-off approach can be applied in an attributional LCA, while the end-of-life recycling method, the 50/50 method, and the waste mining method are substitution methods in a consequential LCA. This framework is not only applicable to recycling situations, but also to co-production and energy recovery, and considers different LCA goals. We apply the framework of Chapter 3 to current official guidelines with the purpose to identify the degree of consistency in their proposed allocation procedures. This review has been published as (Schrijvers et al 2016b). Two additional guidance documents are reviewed in this chapter: a whitepaper of PE International on “Harmonization of LCA methodologies for metals” (PE International 2014) and the newly developed Circular Footprint Formula (Zampori et al 2016), which is an updated version of the 50/50 method of the PEF Guide.

### 2. Methods

In this section, it is discussed which guidelines are selected, and against what review criteria they are reviewed.

#### 2.1. Systematic framework for allocation

The framework that was developed in Chapter 3 is comprehensive due to the inclusion of a large range of LCA goals. In Chapter 3, it was considered that allocation can be avoided in a process-oriented by applying system expansion, while this is not an option in a product-oriented LCA. In the latter, the aim is to identify the impacts of a specific product and allocation is required. Most guidelines do not differentiate between process-oriented and product-oriented LCAs. Therefore, the framework of Chapter 3 is simplified to focus only on product-oriented LCAs. This framework is depicted in Figure 4-1. From Chapter 3 it appeared that an LCA that aims to identify a product’s accountability for impacts should apply an attributional LCA, while a consequential approach is suitable for an LCA that focuses on the impacts that are caused by a product. In consequential LCA, the substitution of processes is modeled by marginal data. The framework of Figure 4-1 is used for the critical review of this chapter.

#### 2.2. Selection of guidelines

The choice of guidelines is based on recent reviews (Zamagni et al 2008; De Camillis et al 2013; Allacker et al 2014), as well as guidelines referred to by the PEF Guide, which are regarded as major contributors in this field. This leads to the following selection: ISO 14044 (ISO 2006a) and ISO/TR 14049 (ISO 2012), the ILCD Handbook (European Commission 2010), BP X30-323-0 (AFNOR 2011), the PEF Guide (European Commission 2013), ISO/TS 14067 (ISO 2013), PAS 2050 (BSI 2011a) and the Greenhouse gas protocol (WRI and WBCSD 2011). Furthermore, General Programme Instructions for the International

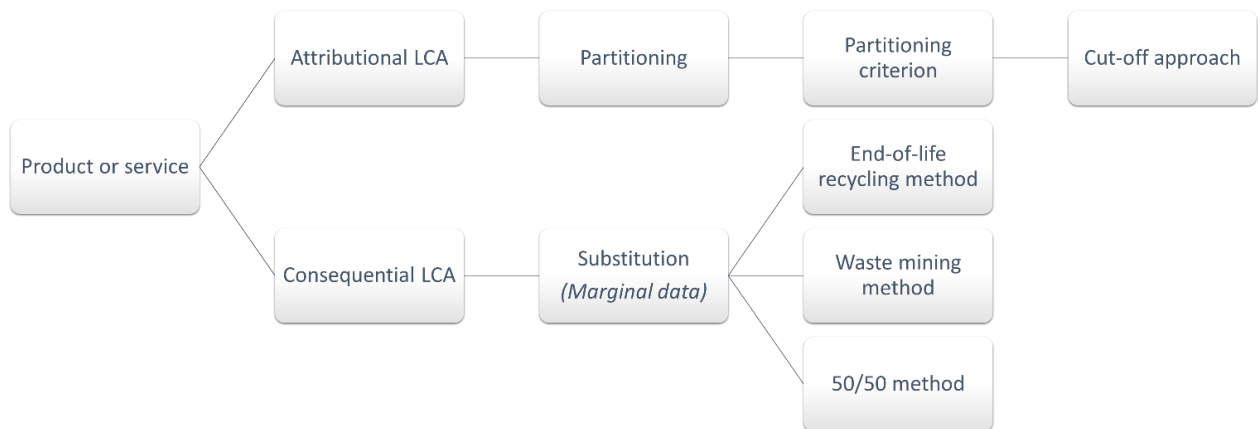


Figure 4-1 Systematic framework for allocation for product-oriented LCAs (based on Figure 3-10 of Chapter 3)

EPD® System (The International EPD® System 2013b) and Guidance for Product Category Rule Development (The Product Category Rule Guidance Development Initiative 2013) have been considered as relevant documents in the development of a common approach. These documents give guidance on an overarching level and enable the inclusion of a product perspective. The REAPro method (Ardente and Mathieux 2014) and the Ecological Footprint Standards (Global Footprint Network 2009) are excluded from this review as the first method is not designed to calculate a product's LCA and the latter one does not give guidance on allocation.

### 2.3. Review criteria

The choice of allocation procedure can greatly influence the results of an LCA (Baumann and Tillman 2004; NCASI 2012), and should, therefore, be well-founded. As different guidelines provide different methods, the LCA practitioner can often apply the method that leads to the most favorable results. Providing consistent guidance avoids biased results due to the chosen allocation method. Although other reviews have studied the guidelines from this review as well (e.g. (Allacker et al 2014; Manfredi et al 2015)), consistency has often been measured by the mere existence of a recommendation on allocation, disregarding its methodological correctness. Instead, we consider that consistent guidance aims to be coherent, following logical reasoning, and providing relevant answers to the LCA goal. Therefore, this review focuses on the consistency of the guidelines, since a lack of consistency could make the results arbitrary and disables a good representation of reality. From the reasoning that was applied to develop the framework Chapter 3, five review criteria were derived:

1. *Consistency between reuse, recycling, energy recovery, and co-production.* Is a single approach applied to all multifunctionality problems?
2. *Consistency between the LCA goal and the proposed method.* Is it recognized that for different LCA goals different allocation procedures could be appropriate?
3. *Consistent application of the attributional and consequential approaches.* Is substitution only applied in consequential LCA? If system expansion is applied, are average market data used in attributional LCA and marginal data in consequential LCA?
4. *Consideration of the market situation of the material.* If substitution is applied, either the waste mining method or the end-of-life recycling method calculates the net impact. Is the market situation of the material taken into account in the choice of substitution method?
5. *Consistent approach for open-loop recycling with and without loss of inherent properties.* If genuine closed-loop recycling takes place, no processes are shared with other product systems, and therefore no allocation procedure is needed (ISO 2012). Besides, in Chapter 3 it was discussed that all allocation procedures will lead to the same results in the case of closed loop recycling. Open-loop recycling while maintaining the inherent material properties – e.g.

via recycled material pool – is sometimes considered as closed-loop recycling as well (ISO 2006a; ISO 2012). However, following our interpretation of partitioning in attributional LCAs, this appeared to be only justifiable in the case when the recycled content equals the end-of-life recycling rate, and no quality losses take place. Considering this, are the impacts of all types of open-loop recycling calculated according to the same procedure?

Some review criteria seem to show overlap. Although open-loop recycling with and without loss of inherent properties are both forms of recycling, criterion 5 is considered separately from criterion 1. If a product is recycled in an open loop, while the inherent properties are maintained, the results might be the same as when closed-loop recycling would have been applied. This is however only the case at certain conditions, which is assessed by criterion 5. Also criterion 2 and 3 seem to show overlap, as the choice of attributional or consequential LCA is dependent on the LCA goal. However, even if the existence of different modeling methods is recognized, the LCA method can be incorrectly or inconsistently applied. Therefore, this is assessed by two separate review criteria.

### 3. Results

The guidelines are reviewed in the chronological order of publication. The numbered paragraphs correspond to the review criteria as defined above. The results of the review are summarized in Table 4-1.

#### 3.1. ISO 14044:2006 and ISO/TR 14049

The allocation hierarchy of ISO 14044 has been presented in Chapter 2. ISO 14049 applies the same hierarchy and gives practical guidance on applying the procedures.

1. The stepwise procedure for allocation in the ISO standard can be applied to co-products, reuse, recycling, material recovery and energy recovery.
2. The ISO standard does not explicitly distinguish procedures for attributional and consequential modeling.
3. Several interpretations exist of the ISO 14044 standard (Zamagni et al 2008). System expansion, which is the preferred solution to avoid allocation, can be interpreted literally, i.e. by including the additional functions of the co-products in the product system. However, several LCA practitioners consider system expansion as a synonym for substitution (Heijungs 2013), which is supported by the original explanation in ISO 14041 (Heijungs and Guinée 2007; Weidema 2014a). Besides, ISO/TR 14049 refers to the use of marginal data when system expansion is applied, which indicates a consequential approach. ISO/TR 14049 shows an application of the substitution method, which can be applied *“for a product specific consideration”*. Although substitution could in theory always be applied, for this method the requirement is given that the primary production process and the recycling process in the product system under study are similar to these processes in the rest of the market, and that the inherent properties of the primary and the secondary material are identical or similar (ISO 2012).

If the recycled material undergoes a change in its inherent properties, an open-loop allocation procedure should be applied. This may also be the case for the first use of primary material (ISO 2006a). However, it is unclear what *“an open-loop allocation procedure”* comprises (Zamagni et al 2008). We interpret the *“open-loop allocation procedure”* as the same allocation procedure that is applied to co-products, due to (1) the statement that the same allocation procedures apply to co-production, recycling and reuse (see criterion 1), and (2) the statement that the need for allocation is avoided in case of open-loop recycling where no changes occur in the inherent properties of the material. Following the general allocation hierarchy, when allocation cannot be avoided, partitioning is applied, based on physical relationships (in the case of co-production) or physical properties (in the case of recycling). Partitioning reflecting physical relationships could be interpreted as modeling the effects of the production of a product (Ekvall and Finnveden 2001),

which can only be applied in the case of combined production (Azapagic and Clift 1999). The term “partitioning” could be interpreted as “substitution” (see for example (European Commission 2013)). As this is not explicit, it is possible to interpret ISO 14044 and ISO 14049 as being fully consequential. However, partitioning could also be interpreted as the artificial distribution of the inventory across the co-products (Guinée 2002), i.e. the attributional application of partitioning. The same could be concluded regarding partitioning reflecting other relationships, e.g. economic value.

The possibility of multiple interpretations is due to lack of clarity and proper guidance of the ISO standard (Zamagni et al 2008; Weidema 2014b), which is a potential source of inconsistencies. Due to the restrictions put on the application of substitution, and the possible different interpretations regarding the “open-loop allocation procedure” if these restrictions are not fulfilled, attributional and consequential elements could both be applied while following the ISO standard.

4. ISO 14049 indicates that system expansion should be done by including the additional functions using their marginal supplier or technology. Therefore, it could be argued that the market situation is taken into consideration.
5. As stated at criterion 3, open-loop recycling while the inherent material properties are maintained is modeled by a “closed-loop allocation procedure” (ISO 2006), which could be illustrated as a substitution approach (ISO 2012). If open-loop recycling is applied with a change in the inherent material properties, an “open-loop allocation approach” is applied, which could be interpreted as substitution as well. In this case, there is no inconsistency between the different situations of open-loop recycling. However, the “open-loop allocation approach” could also be interpreted as a form of partitioning. Based on a common interpretation of the partitioning method, we showed in Chapter 3 that the inventory in an open-loop recycling system equals the inventory of a closed-loop recycling system after several recycling loops, under the conditions that (1) the primary production process, the recycling process and the waste treatment in the life cycle under study are similar to these processes in the rest of the market, (2) the average recycled content and end-of-life recycling rate in the specific material market are equal, and (3) there are no quality losses. Although the first condition is mentioned in ISO/TR 14049, the given example in this document does not fulfill condition 2. Whether condition 3 is fulfilled depends on the definition of “inherent properties”. No explanation is given on how these are defined (NCASI 2012; Geyer et al 2015). The example of the closed-loop approach in ISO 14049 mentions the use of recycled material, and ISO 14044 states that the closed-loop approach can be applied when “the use of secondary material displaces the use of virgin (primary) materials”. However, the “closed-loop approach” is sometimes referred to as equivalent to the end-of-life recycling approach (e.g. (Atherton 2007; Ligthart and Ansems 2012)), although the end-of-life recycling method does not consider a consumption of recycled material. Again, the possibility of multiple interpretations in the guidance of ISO 14044 and ISO 14049 could lead to inconsistencies between open-loop recycling with the maintenance of inherent properties and open-loop recycling with the loss of inherent properties.

### 3.2. The ILCD Handbook

The ILCD Handbook (European Commission 2010) provides detailed guidance to the ISO 14040 and 14044:2006 standards. Three situations are described corresponding to different LCA goals. Situation A gives micro-level decision support, e.g. on a product level. Consequences that take place in the background system are small and do not lead to structural changes of installed capacity. Structural changes are here referred to as the installation of new production plants or technologies. However, it is stated that the influence of small-scale decisions on long-term structural changes needs to be better understood. Situation B supports decisions on a meso/macro-level scale, e.g. policy development, including large-scale consequences in the background system, due to structural changes in installed capacity. Situation C represents a retrospective accounting method with no interest in additional consequences in the background system. Situation C1 includes existing benefits outside the system

boundaries, e.g. due to recycling, while these effects are ignored in C2. Each situation follows a specific method for allocation in LCA.

1. Very detailed guidance is given on how substitution and partitioning should be applied, using the same methods for co-production, recycling, reuse, and energy recovery.
2. The situations in the ILCD Handbook each support a goal definition and the need for corresponding data for attributional and consequential LCAs is acknowledged.
3. LCAs that are conducted to support decisions with an interest in the consequences, i.e. Situations A and B in the ILCD Handbook, ask for a consequential approach (De Camillis et al 2013; Ekvall et al 2016). It is acknowledged that in Situation A, substitution is preferably applied using the short-term marginal market mix. However, to increase the practical applicability of Situation A, simplifications are done that allow the substitution of the average market mix and partitioning. These simplifications introduce inconsistencies in the approach, as attributional elements are included. This is also valid for Situation C1. However, Situation B and C2 do propose allocation methods that are consistent with the goal definition. Substitution using marginal processes and systems is applied in Situation B – although incremental data could, in this case, be even more appropriate (Ekvall et al 2016). In Situation C2, which asks for an attributional LCA, partitioning is applied.
4. For substitution, the term *recyclability substitution* is introduced, which allows substituting the actually avoided process: primary production or waste management. Elaborate guidance is given to determine the avoided process, which is dependent on the market situation.
5. A differentiation is made between “open loop - same primary route” recycling and “open loop – different primary route” recycling, which corresponds to the maintenance of inherent properties in ISO 14044. In attributional LCA, for “open loop – same primary route” a method is given that calculates the average inventory per life cycle after an infinite number of recycling loops. “Open loop – different primary route” recycling is modeled by partitioning. This could lead to the same results when the recycled content equals the end-of-life recycling rate and no quality losses take place. As this is not given as a requirement, this differentiation could lead to inconsistencies.

### 3.3. BP X30-323-0

The French AFNOR published the standard BP X30-323-0 (2011) as a guide for “good practice” for calculating and communicating the environmental impacts of a product throughout its life cycle. The environmental communications should enable the comparison of environmental impacts between products from the same category.

1. Co-product allocation is done according to, in order of preference, (1) process subdivision, (2) subdivision according to physical relationships, (3) subdivision by including the co-functions by expanding the system boundaries, (4) subdivision according to economic value or (5) subdivision according to a combination of these rules (AFNOR 2011). AFNOR proposes the cut-off approach for closed-loop recycling and substitution formulas for open-loop recycling, all including an extra term for energy recovery. In summary, different approaches are applied to different multifunctionality problems.
2. The objective of the standard is to inform consumers during their decision-making processes. Both attributional and consequential LCA could be applied in the decision-making process: attributional LCA to increase knowledge about the current environmental performance of the part of the product system that is allocated to the product, and consequential LCA to learn about the effects of a purchase (Tillman 2000; UNEP/SETAC Life Cycle Initiative 2011). No clear distinction is made between these levels of decision-making, neither is a choice between attributional and consequential LCA made. Elements of both approaches are proposed, and the proposed allocation procedure is therefore not adjusted to the LCA goal.
3. Although it is not straightforward how “subdivision according to economic value” should be interpreted, Weidema (2001) identified that economic allocation is typically applied in



attributional LCAs. While an attributional approach could be applied for co-product allocation, for open-loop recycling the proposed formulas are in accordance with consequential modeling, although average market data, instead of marginal data, are used for the substituted processes.

4. In the case of open-loop recycling, the proposed formula depends on the extent of the diffusion of recycled material in the market. If the market is in disequilibrium because the secondary materials are fully used, the production of recycled material should be stimulated by applying the end-of-life recycling method. This formula applies, among others, to steel, aluminum, and glass. If the market does not show disequilibrium, i.e. there is a lack of recycled material or the recycled material is not being used, the 50/50 method should be applied. The 50/50 method allows the benefits of recycling being equally distributed among the producer and the consumer of the recycled material and is mainly applicable to plastics (AFNOR 2011). Very detailed guidance is given on how to take energy recovery and waste management into account. In Chapter 3 we discussed that energy recovery can, similar to recycled materials, also be regarded as a co-product. Treating them separately leads to an apparent preference for energy recovery over the production of recycled material, as the latter is only credited for 50% (Eurofer et al 2013). However, because the 50/50 method is in this guideline only applied to materials for which a demand or supply is not yet fully established, energy recovery might have the preference and is hereby treated by the end-of-life recycling method. By proposing different formulas for different material markets, it is recognized that recycling activities do not necessarily lead to a reduction of environmental impacts in all situations. However, the 50/50 formula proposed by AFNOR does not explicitly mention the fact that the recycled content substitutes waste in the *previous* life cycle instead of in the current life cycle, and quality losses are not taken into account.
5. No distinction is made between open-loop recycling with or without a change of inherent properties. The methods for different applications of open-loop recycling are therefore consistent.

### 3.4. PAS 2050

The British Standards Institution (BSI) developed the Publicly Available Specification 2050 (PAS 2050) as a consistent method to quantify the greenhouse gas emissions of goods and services (BSI 2011a).

1. Allocation of co-products should be solved by subdivision, system expansion (using average data) or if necessary by physical or economic partitioning. The allocation method should be applied uniformly. A formula is given for the case of reuse, for a given number of reuse loops (or trip numbers, this is not clearly specified). Although this method resembles the multi-recycling approach (Neugebauer and Finkbeiner 2012), the inventory related to the preparation activities for reuse might be overestimated ( $n-1$  recycling activities take place for  $n$  trip numbers). Reuse could, however, be interpreted as analogous to recycling. Recycling is separately considered from co-production and reuse. When the inherent material properties are maintained, the end-of-life recycling method is recommended. The cut-off approach is applied to situations where the inherent material properties are not maintained, or when the product under study contains many inputs and outputs of different recycled materials, as the equation can get quite complicated. For energy recovery, a method that corresponds to the end-of-life recycling method is recommended.
2. The objective of PAS 2050 is “to provide a common basis for GHG emission quantification that will inform and enable meaningful GHG emission reduction programmes”. This objective could be interpreted as the identification of accountability for impacts as well as decision support on the implementation of measures to reduce global GHG emissions. Therefore, both an attributional and a consequential approach could be appropriate. An attributional approach is applied by the guideline. However, emission reduction programs could benefit from consequential LCA as well, to assess the effects of the applied reduction strategies on global greenhouse gas emissions.
3. The allocation procedures for co-production and open-loop recycling (where inherent properties are lost) are attributional by nature. However, partitioning based on physical properties can be applied to co-products, while only the cut-off approach is applied in the case of open-loop recycling. Although the cut-off approach is a form of partitioning, physical or economic properties

could be a basis of partitioning in the case of recycling as well – as discussed in Chapter 3. Furthermore, by recommending the end-of-life recycling method, consequential elements are introduced.

4. The Guide to PAS 2050 (BSI 2011b) gives more specification for when to use the cut-off approach (e.g. in the case of downcycling or a high supply of recycled material) or the end-of-life recycling approach (e.g. in the case of direct substitution or a saturated market). However, the cut-off approach and the end-of-life recycling method have different implicit assumptions, which was discussed in Chapter 3, and they are based on a different value system (Frischknecht 2010). Where substituted parts of the system are considered in the end-of-life recycling method, these fall outside the scope of the cut-off approach. Although differences in material markets are taken into account, the inherent difference in the proposed methods disables comparisons between different materials. Besides, the guideline does not explicitly exclude the possibility to apply the end-of-life recycling approach in one life cycle, and the cut-off approach in a subsequent life cycle. In this case, double counting of credits and omission of impacts take place.
5. The cut-off approach, the end-of-life recycling method and the reuse formula only provide the same results when the recycled content and the end-of-life recycling rate are the same, and if recycling does not lead to quality losses. Therefore, there is no consistency between the approaches for different situations of open-loop recycling.

### 3.5. Greenhouse Gas Protocol

The Greenhouse Gas (GHG) Protocol (WRI and WBCSD 2011) is developed by actors from businesses, non-governmental organizations and governments, represented by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The GHG Protocol provides standards based on consensus between several stakeholders and academic institutes for accounting and reporting of greenhouse gas emissions.

1. In the GHG Protocol, co-product allocation is avoided by subdivision or expanding the functional unit by including the co-functions. Substitution can be applied when companies have direct knowledge of the use of the co-product. If partitioning cannot be avoided, examples are given on when to apply physical or economic partitioning. In the case of recycling, the closed-loop approximation (referred to as the end-of-life recycling method) or the cut-off approach are proposed. In Section 3.1 we already discussed the potential difference between the end-of-life recycling method and the closed-loop approximation as described in ISO 14049. The cut-off approach is used when no end-of-life recycling takes place, in a market with a higher supply than demand for the recycled material, when the company has control over the recycled content, or when the time frame of the life cycle is very long. The end-of-life recycling method is applied when the inherent properties of the primary material are maintained, when the recycled content is unknown, when the demand for recycled material exceeds its supply, and in a short or well-known time frame of the use stage. Downcycling is taken into account by including a correction factor. Although system expansion and substitution are both recommended for co-production and recycling, applying the cut-off approach only to some recycling scenarios makes the approach not consistent between co-production and recycling.
2. The standard is designed "to promote best practice GHG accounting and reporting". It is stated that "The requirements and guidance in this standard follow the attributional approach of life cycle accounting". Several uses of product inventories are identified, of which some benefit from an attributional approach (e.g. meeting GHG regulations etc), although some applications might benefit from a consequential approach (e.g. choosing between alternative options to meet reduction targets). However, it is acknowledged that different LCA approaches could be useful for different LCA goals.
3. The GHG Protocol uses an attributional approach and therefore recommends to substitute with average market data. However, we apply a strict separation between attributional and consequential LCA and identify substitution to be a consequential element. System expansion by



increasing the functional unit to include the recycled material without the subsequent substitution step would make the approach more attributional.

4. The potential benefits of recycling are well represented by the consideration of the market situation. However, similar as for the PAS 2050 guideline (Section 3.4), the combination of the cut-off approach and the end-of-life recycling method leads to inconsistencies.
5. Substitution is applied for open-loop recycling where inherent properties are maintained, and the cut-off approach is applied in other recycling situations. Following the same reasoning as in Section 3.4, the approaches for different open-loop recycling situations are inconsistent.

### 3.6. EN 15804:2012

The European standard EN 15804:2012 for sustainability of construction works provides core Product Category Rules (PCR) to enable the development of comparable Environmental Product Declarations (EPDs) of construction products, services, and processes (CEN 2012). PCRs are sets of specific rules, requirements, and guidelines for developing Type III environmental declarations (e.g. EPDs) for one or more product categories (ISO 2010). These declarations are quantitative LCA-based claims regarding the environmental impact of a product, good or service (European Commission 2013). The EN 15804:2012 standard divides the stages of the life cycle in modules: Module A represents the production stage, Module B the use stage and Module C the end-of-life stage. Benefits and loads beyond the system boundaries are included in Module D.

1. Co-product allocation is done by subdivision, or, if relevant data are not available, by partitioning based on physical properties if the market prices are comparable, or on economic value if the market prices vary more than 25%. If the co-products share a relevant inherent property, partitioning should, however, be based on this. Allocation of recycled products is handled differently. Waste processing up to the end-of-waste state (where the material has a positive market value) is included in Module C. Further processing of consumed recycled material is part of Module A. Therefore, closed-loop recycling is calculated by Modules A to C. These modules represent the cut-off approach. Recovered energy and recycled materials that can replace primary materials in a subsequent life cycle in a different product system can be included in an optional Module D. Module D includes the impacts related to further recycling steps that make the recycled material equivalent to the substituted material, and the environmental benefits of avoiding the primary production of this material. If no functional equivalence with the substituted product is achieved, a value-correction factor is applied, which is not further specified. Only the impacts and benefits of the *net* end-of-life recycling rate – the end-of-life recycling rate minus the recycled content – are included. If the recycled content is higher than the end-of-life recycling rate, this could, therefore, lead to an increased environmental impact of the product. Although Module A to C represent recycled materials according to the cut-off approach, the inclusion of Module D changes the approach to the end-of-life recycling method. This is demonstrated in Chapter 3.
2. One of the objectives of the standard is to provide data for stand-alone EPDs. According to the General programme instructions for the International EPD® system 2.01 (see below), an attributional approach should be applied. This has also been suggested by Tillman (2000), although a consequential approach could be appropriate if EPDs are designed to inform customers about the influence that their purchase would have on environmental impacts (Weidema 2003). Although co-products are allocated via an attributional approach, no explicit modeling choice is made regarding recycling.
3. By recommending the cut-off approach and the end-of-life recycling method, using average market data, attributional and consequential elements are combined.
4. As Module D is optional, LCA practitioners can choose between the cut-off approach and the end-of-life recycling method depending on which method calculates the lowest environmental impact. Therefore, environmental credits are attributed according to the convenience of the LCA practitioner instead of representing actual environmental benefits by considering the market

situation. This could even lead to double counting, if the product system that produces recycled material includes the future benefits in Module D, while the consumer of the material applies the cut-off approach. The approach of EN 15804 is however embraced by the metals sector (Eurofer et al 2013). The end-of-life recycling method takes multiple recycling loops into account, which can be relevant for metals (Atherton 2007). However, multiple recycling loops can also be considered in attributional LCA, by calculating the impact of a material that has been recycled multiple times in the past (see Chapter 3).

5. No differentiation is made between open-loop recycling with and without maintenance of inherent properties. Therefore, Module D can be applied in all cases of open-loop recycling.

### 3.7. ISO/TS 14067:2013 – Carbon footprint of products

ISO/TS 14067 (ISO 2013) is based on, among others, ISO 14040 and ISO 14044 and provides more specific requirements for the quantification and communication of the carbon footprint of products and services. The procedures to deal with allocation are taken from the ISO 14044 standard.

1. ISO 14067 gives practical examples on how to apply allocation to recycled materials. For closed-loop recycling and open-loop recycling while maintaining the inherent properties, a formula is given that represents the end-of-life recycling approach. For open-loop recycling, it is suggested to apply process subdivision of the recycling process with the use of the cut-off approach. If the impacts related to the extraction and processing of the primary material need to be shared between the primary and secondary use of the material, system expansion or partitioning is applied, following ISO 14044. More elaboration is given on economic partitioning using a market-price based allocation factor  $A$ , which is the ratio between the global market price of the recycled material and the global market price of the primary material. A long-term average can be used to determine the market price. When recycled material is produced in open-loop recycling, the share of the impacts of the primary extraction and processing that is attributed to the recycled material has the value of  $A$ . Therefore, if the market prices are equal and  $A = 1$ , all the impacts are attributed to the recycled material. This formula seems similar to the end-of-life recycling method. However, in this formula, the emissions of the primary production in the current life cycle are subtracted, instead of the emissions of the primary production in the subsequent life cycle. This method differs from the economic partitioning method as described in Chapter 3, where an equal market price would lead to a distribution of the impacts of primary extraction and processing of 50% to the primary material and 50% to the recycled material. The consumption of recycled material in open-loop recycling is represented by the same formula, allocating the remaining environmental credits by including the correction factor  $(1-A)$ . Although ISO 14067 gives an extensive elaboration on recycling, and the examples that are given differ from the approach for co-products, the general guidance for allocation is taken from ISO 14044 and is applicable to co-production and recycling.
2. The goal of a Carbon Footprint study as described by the technical specification is to calculate the potential contribution of a product to global warming. It is not clearly stated whether the potential contribution on global warming is assessed from an accounting perspective or an effect-oriented perspective. Which LCA approach would be appropriate depends on the intended application of the study, e.g. to apply environmental taxation or to decide on a purchase of a product that causes low environmental impacts. The recommendations in the specification do not consider multiple application types.
3. The proposed partitioning approach is presented as one possible interpretation of the ISO standard. Although the approach seems similar to the end-of-life recycling method, no impacts or benefits from beyond the product system are included. A substitution rationale is only applied for open-loop recycling while maintaining the inherent properties of the material. Furthermore, ISO/TS 14067 refers to ISO/TR 14049, where system expansion is applied using marginal data. Therefore, we conclude that in this interpretation of the ISO standard attributional and consequential elements are combined.

4. Even though the partitioning approach takes the market situation of the recycled material into account, this is inherent to economic partitioning. However, by referring to ISO 14049, system expansion is applied with marginal market data. Therefore, the market situation of the material is indirectly considered.
5. The procedures for open-loop recycling with and without maintenance of inherent properties differ by the factor  $A$ . Therefore, these methods are different if the market-price ratio between the recycled and the primary material is lower than 1. The market-price ratio and the maintenance of inherent properties are not necessarily correlated, which makes the approaches inconsistent between different open-loop recycling situations.

### 3.8. PEF Guide

The Product Environmental Footprint (PEF) Guide (European Commission 2013) is developed “to provide a common basis for measuring and communicating environmental performance”, in response to the proliferation of methods for this purpose (Galatola and Pant 2014). It gives guidance on calculating the PEF of a good or a service as well as on defining product specific Product Environmental Footprint Category Rules (PEFCRs), which enable the comparison of different PEFs (European Commission 2013). PEFCRs give further guidance for PEF studies for specific product types, by further specifying requirements stated by the PEF Guide, or by making choices that are left open in the PEF Guide. In some cases, the PEF Guide and the ILCD Handbook do not provide the same recommendations. When the guidelines differ, the PEF Guide should be followed (European Commission 2013).

1. The guidance for co-product allocation follows the ISO hierarchy while including substitution procedures: a co-producing multifunctional system should be solved by subdivision or system expansion. If this is not possible, direct substitution or partitioning based on underlying physical relationships should be applied, where partitioning is referred to as substitution. When no physical relationships can be identified, indirect substitution or partitioning based on economic values can finally be applied. Indirect substitution represents the situation where it is not entirely certain which process is substituted. The marginal or average market-mix is then used as data source for the avoided process. PEFCRs can further specify how to solve multifunctionality problems. To take recycling and energy recovery into account, a mandatory formula is provided to calculate the *Resource Use and Emissions Profile* per unit of analysis of the end-of-life situation (European Commission 2013). The formula is based on the standard of AFNOR and is a representation of the 50/50 method. It is presented as a compromise between different recycling formulas from other methods, to be used in all situations (Galatola and Pant 2014). Contrary to the 50/50 formula as presented by AFNOR, energy recovery is also credited for 50% in the updated PEF formula (European Commission 2014c), and the recycled material consumption explicitly leads to avoided waste management in the previous life cycle. Downcycling is taken into account by a quality-correction factor, based on the limiting physical property or the market price. This should be specified in the PEFCRs (Galatola and Pant 2014).
2. The goal stated above does not specifically require an attributional or a consequential approach. Intended applications – e.g. identification of environmental hotspots, marketing, benchmarking and environmental labeling – can benefit from either LCA approach. However, the PEF Guide takes elements from both attributional and consequential LCA (De Camillis et al 2013; European Commission 2013). It is acknowledged that “*the applied LCI methods and methodological choices [should be] in line with the goal and scope of the dataset, especially its intended applications as support to decisions*” (European Commission 2013). However, this requirement applies only until the end of 2015. After this date, data quality is considered high if there is full compliance with the (mandatory formula of the) PEF Guide. Therefore, the need for different types of LCA is not considered in this guideline. This is similar to the ISO 14044 standard, which has already led to much criticism (Curran 2007; Zamagni et al 2008).

3. Although the PEF Guide takes elements from both attributional and consequential LCA, solutions to solve multifunctionality mostly refer to substitution (using marginal market data), which is typically consequential. However, economic partitioning in proportion to the relative economic values of the co-products is also proposed (as a last resort), which is an attributional approach.
4. Although in the AFNOR guideline three different formulas are proposed for different recycling situations, only one is taken over by the PEF Guide. The approach of AFNOR was perceived as *“too complex to be directly used in the broad application of the environmental footprint methods”* (Galatola and Pant 2014). However, the 50/50 method implies that both the consumption and the production of recycled material lead to a reduced environmental impact. For several materials, this is not the case, e.g. if there is no demand for the recycled material or if all the available recycled material is already fully consumed. Crediting nonetheless for the production and the consumption of recycled material does not give a good representation of the (reduced) environmental impacts related to that product. Considering that in the PEF Guide the 50/50 method is applied to all materials, this could, therefore, lead to discrepancies between the calculated environmental benefits and the actual benefits.
5. The 50/50 method is valid for open-loop recycling with and without loss of inherent properties.

### 3.9. General programme instructions for the International EPD® system 2.01

The International EPD® (Environmental Product Declaration) System enables organizations to publish environmental information of their products according to several ISO standards. The General programme instructions for the International EPD system (2013) is based on ISO 14025 (ISO 2010) and claims to be in accordance with ISO/TS 14067.

1. It is argued that multifunctionality problems cannot be solved via system expansion due to the book-keeping approach and the concept of modularity of the EPD system (The International EPD® System 2013b). If process subdivision is not possible, partitioning takes place based on physical relations or economic value, for which the reference values shall be explained in PCRs. The document refers to EN 15804:2012 for further PCR information. In the case of recycling the ‘polluter pays’ method is applied, which corresponds to the cut-off method and could be interpreted as “process subdivision” (ISO 2013). If another method is deemed more suitable, it can be justified in the PCR document. The additional environmental benefits can then be presented in the EPD under “Additional environmental information”. If multiple end-of-life options exist, calculations can be done for different scenarios. If waste is sent to a facility that prepares it for a second life, e.g. energy recovery or composting, the impacts related to this waste treatment are suggested to be attributed with a 50/50 economic partitioning approach to the waste treatment service and the recovered energy.
2. As already stated in Section 3.6, whether an attributional or a consequential approach is more appropriate for EPDs, depends on the goal of EPDs. If the goal is to inform the consumer about the impacts that are attributed to the product, an attributional approach would be useful, while if the objective is to inform the consumer about the influence of his purchase on environmental impacts, a consequential approach should be used (Weidema 2003). An attributional approach is applied to reflect the present situation to the best extent possible, following operational and user demands. The proposed method is therefore adapted to the goal of the study.
3. Due to the attributional nature of EPDs, partitioning cannot be avoided with substitution. The document applies the attributional approach therefore consistently.
4. Because substitution is not proposed as a solution to solve multifunctionality, the market situation of the recycled material is not relevant. This criterion is therefore not applicable (N/A) to this document.
5. No distinction is made between open-loop recycling with and without maintenance of inherent properties, which makes the approach consistent between the two situations.

### 3.10. Guidance for Product Category Rule Development

The guidance document for PCR development is written in response to the need for specific guidance for product groups on life cycle assessment (The Product Category Rule Guidance Development Initiative 2013). The document can be used as supplementary guidance to existing standards that refer to the development of PCRs.

1. According to the guidance document, co-product allocation should be avoided by subdividing the processes, where possible. Which processes are subdivided and how, should be specified in the PCR. If partitioning is done based on physical relationships, the relevant physical relationships that should be considered and the relevant partitioning rules are specified in the PCR. This is also the case for other relationships on which partitioning is based. Regarding recycling, PCRs should communicate accounting rules if these are not yet defined by the LCA-based claim standards. Co-production and recycling are therefore considered to be different multifunctionality problems.

The score for the other review criteria depends on the choice of supplementary standard. Therefore, the other review criteria are not applicable (N/A) to this guidance document.

### 3.11. Harmonization of LCA Methodologies for Metals

PE International (2014) developed a guidance document for a harmonized approach to Life Cycle Inventory and Impact assessment for the metals and minerals industry. Harmonization would enable to align LCA practices within the industry and to strengthen the position of the sector in further discussions with regulators, database providers and external stakeholders (PE International 2014).

1. System expansion – in the sense of substitution – is the preferred approach for co-production. However, it is acknowledged that single-output processes are not always available for metals. In that case, partitioning should be applied. It is stated that partitioning is by preference based on mass when the economic value of the co-products is similar, due to fluctuating prices. However, the mass is calculated based on the metal content in the co-products rather than the total product that includes wastes as well. If precious and base metals are mined together, economic allocation is preferred, as this represents the purpose of the processing operations. We would like to make the side-note that, under the conditions described in the document, allocation based on mass or economic value will result in similar allocation factors. For recycling situations, the end-of-life recycling approach is recommended. In the case of downcycling, the value-corrected substitution approach of Koffler and Florin (2013) can be applied. Due to the fact that substitution of an allocated primary product can be modeled in the case of recycling but not in the case of co-production, the approach is not consistent.
2. It is not clearly described what purposes the inventory data based on this document can serve. However, it is mentioned that the document follows an attributional approach.
3. Partitioning and substitution are both recommended as allocation procedures. Therefore, attributional and consequential elements are mixed.
4. The document is based on earlier work of Atherton (2007). In this paper, the end-of-life recycling approach is recommended for metals due to the high demand for recycled metals. Only the additional supply of recycled metals is deemed to lead to environmental benefits. Therefore, we could conclude that the market situation of the material is taken into consideration.
5. There are some differences between the value-corrected substitution method and the end-of-life recycling method. The latter usually models a displacement of a primary material related to the properties of the recycled material. This can be a completely different material in the case of open-loop recycling. The value-corrected substitution method models a displaced production of the primary material that was used in the product. This can be a different type

of material than the material that is actually displaced. However, in the specific case of metal recycling, the approaches could be considered similar.

### 3.12. Circular Footprint Formula

After publication of the PEF Guide (see Section 3.8), the European Commission has continued to work on an improved end-of-life formula. Recently, a new formula has been developed: the Circular Footprint Formula (CFF) (Zampori et al 2016). In this formula, the 50/50 ratio is replaced by an allocation factor that represents the market situation of the material. This factor can vary from 0.2 to 0.8 for recycled products and has a default value of 0 for recovered energy, which corresponds to the end-of-life recycling method.

1. The document that presents the CFF does not provide updated guidance on co-products. The original guidance of the PEF Guide applied co-product allocation by substitution or economic partitioning. Substitution could be represented by the CFF for an allocation value of 0. However, the demand for co-products could be low as well, which could be better represented by a higher value for the allocation factor. As this is not discussed, the method is considered inconsistent between recycling and co-production.
2. Although the CFF models recycling in a consequential manner, the updated PEF Guide does not make a clear choice between attributional and consequential LCA.
3. Allocation of co-production can be done in a consequential or in an attributional manner. Therefore, the same analysis is valid as for the original PEF Guide.
4. The updated formula includes a factor for different market situations of recycled material.
5. The CFF is, similar to the original End-of-Life Formula of the PEF Guide, applicable to all recycling scenarios. Furthermore, the CFF contains updated and corrected quality factors, which has improved the formula in comparison to the original EoL formula.



Table 4-1 Summary of results of the critical review of guidelines

	ISO 14044:2006	ILCD Handbook	BP X30-323-0	PAS 2050	Greenhouse Gas Protocol	EN 15804:2012	ISO/14067	PEF Guide	General programme instructions for the international EPD® system 2.01	Guidance for PCR development	Harmonization of LCA Methodologies for Metals	Circular Footprint Formula
1. Consistency between reuse, recycling, energy recovery and co-production	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No
2. Consistency between the LCA goal and the proposed method	No	Yes	No	Yes	Yes	No	No	No	Yes	N/A	Yes	No
3. Consistent application of attributional and/or consequential approaches	No	Yes/N/A <sup>a</sup>	No	No	No	No	No	No	Yes	N/A	No	No
4. Consideration of the market situation of the material	Yes	Yes	Yes	Yes	Yes	No	Yes	No	N/A	N/A	Yes	Yes
5. Consistent approach for open-loop recycling with and without loss of inherent properties.	No	No	Yes	No	No	Yes	No	Yes	Yes	N/A	Yes	Yes

<sup>a</sup> Due to a simplified consequential approach

#### 4. Discussion

Comparing the guidelines to the framework presented in Chapter 3, it appears that none of them follows the framework on every aspect. The ILCD Handbook and the General programme instructions for the International EPD® system provide most consistent guidance, by following the framework on 4 of the 5 review criteria. The ILCD Handbook is the only guideline that proposes the method here referred to as the waste mining method. Confusing this with the cut-off approach, which is done by several guidelines, leads to large inconsistencies that can easily be solved.

It is remarkable that the majority of the guidelines proposes different advice for co-product allocation and recycling, while recycled products can be regarded as co-products as well (European Commission 2010). A similar distinction can be found between open-loop recycling with and without maintenance of inherent properties, which is applied by several guidelines. Applying one allocation method to certain co-products and another method for other co-products leads to inconsistencies and violations of mass balances (Weidema 2013). The same distinction is visible in guidelines that propose a separate method to deal with energy recovery, such as BP X30-323-0, which leads to the apparent preference for energy recovery over recycling. If instead recycling would be considered as a multifunctionality problem, one allocation methodology can be proposed, consistently applied to all types of by-products. Also reuse is sometimes regarded as a separate problem (BSI 2011a; Allacker et al 2014), while all operations for recycling are applicable to reuse as well.

While the modeling of recycling is very divergent over the guidelines, more consensus seems to exist on co-product allocation. The practical application is more often left to be determined in PCRs. The PEF Guide states that *“PEFCRs should, to the extent possible and recognizing the different application contexts, be in conformity with existing international Product Category Rule (PCR) guidance documents”* (European Commission 2013). The mandatory formula for recycling provided by PEF does however not correspond to the EN 15804 standard, while the metals sector has stated its preference for the method presented in the CEN standard over the PEF Guide (Eurofer et al 2013). Contrary to the metals sector, the plastics sector would benefit from an increased recycled content as well as an increased end-of-life recycling rate (Plastics Recyclers Europe 2012), which makes the formula of the PEF Guide more relevant for this sector than the approach of EN 15804. Galatola & Pant (2014) recognize that different approaches can be valid in different situations, which might appear from current pilot studies. Specific guidance in different sectors can be given in PCRs and PEFCRs, which is already recommended for co-product allocation in the PEF Guide and by Pelletier et al. (2013). For example, PEFCRs could indicate what material properties are relevant for different applications, how the quality of a material can be quantified, and how market prices (e.g. for economic partitioning) could be determined.

Allacker et al. (2014) argue that the strength of the PEF Guide lies in the one-formula-fits-all method. This makes the method easy to apply and enables comparison between LCA studies. However, it implies that the use and the production of recycled material always lead to reductions in the environmental impact. LCA results provided by the 50/50 method, therefore, lead to the appearance of environmental consciousness but do not reflect relevant environmental information.

Although a one-formula-fits-all method could seem to increase the comparability between LCA studies, not all studies are done with the same goal and they should therefore not be compared at all. We proposed a framework that covers multiple LCA goals. Although the methods that are used in different LCA approaches are not comparable, a comparison between attributional and consequential LCA studies should not be pursued in the beginning. Many guidelines do not recognize the existence of different LCA goals and therefore do not propose different LCA approaches. Furthermore, the LCA goal of several guidance documents is not clearly formulated.



It should be noted that all guidelines – with the exception of the ILCD Handbook – aimed to recommend an attributional approach. The fact that it was often recommended to apply substitution suggests that a clear vision was lacking of the impacts and mechanisms that an attributional LCA aims to capture. This was confirmed by a small literature review on the definition of attributional LCA in Chapter 2. Many different definitions exist, and most of them do not support a clear interpretation on what the results of an attributional LCA are supposed to represent. The systematic framework proposed in Chapter 3 is based on the definition for attributional LCA of the UNEP/SETAC Life Cycle Initiative (2011). This definition describes the ideal attributional LCA, which might not correspond to the typical attributional LCA as often applied in reality (Suh and Yang 2014). Attributional LCA as described in the ILCD Handbook, *“includ[ing] all the processes that are identified to relevantly contribute to the system being studied”*, does not explicitly rule out the use of substitution. Suh & Yang argue that LCA approaches should not be regarded from the dichotomous perspective of attributional and consequential. From historical LCA studies, it appears that LCA approaches form a continuous spectrum (Suh and Yang 2014). The fact that attributional and consequential elements are often mixed in LCA practice could indicate that the LCA approaches are not clearly enough described.

The argumentation of the guidelines to apply partitioning or substitution suggests that attributional and consequential approaches are both considered relevant. However, combining elements of the two approaches is not considered as a solution. It can be arbitrary for which multifunctionality problems partitioning or substitution is applied. Furthermore, the results of the LCA become difficult to interpret: due to the fact that the allocation procedure is goal-dependent, it becomes unclear for what LCA goals the results can be used. Efforts on the harmonization of LCA practice, such as the PEF Guide of the European Commission, aim to make the LCA results useful for a broad range of purposes. If a guideline is designed to increase the comparability between products, this could be on an attributional level, e.g. to investigate which product is attributed a larger share of the worldwide environmental impacts, or on a consequential level: what is the impact of a consumers' choice? The motivation of comparison should, therefore, be clearly specified. Applying LCA results in a wider context is only possible if the results are accompanied by a detailed description of the goal and scope. This implies that guidelines should acknowledge that their guidance is limited to this specific goal and scope.

It must be emphasized that the review of the guidelines is based on our interpretation of allocation approaches as described in Chapter 3, as well as on our interpretation of the guidelines. Both areas of interpretation can be subject to discussion. However, if multiple interpretations of the investigated guidelines could co-exist, this could indicate a lack of clarity of the guideline, which is an inherent source of inconsistencies (Zamagni et al 2008; Weidema 2014b).

## 5. Conclusions

In this chapter, we aimed to identify the obstacles for consistent modeling of recycling in LCAs. Several guidelines recommend how to solve this multifunctionality problem by prescribing specific allocation methods. However, there is no one-formula-fits-all method for recycling in LCA. This has already been suggested by, among others, Ekvall and Tillman (1997). This is also indicated by the freedom for interpretation in the ISO standard, the differentiated recommendation of AFNOR, the choice of the 50/50 method and the accompanying argumentation in the PEF Guide, and the pronounced preference of the metals sector.

We have critically reviewed official guidelines against the systematic framework for allocation in LCA that was developed in Chapter 3. The guidelines have been analyzed on their consistency in their recommended allocation procedures. None of the guidelines appears to be fully consistent with the framework. Partitioning is rarely proposed to model recycling in an attributional LCA. If substitution is recommended, the market situation of the material is not always taken into consideration. Of the

analyzed guidelines, the ILCD Handbook provides the most consistent approach by proposing a single allocation procedure for co-production and recycling, and by considering different LCA goals and different market situations. The General programme instructions for the International EPD® system provides consistent guidance by applying a strict attributional approach, although co-production and recycling are not treated as equal multifunctionality problems.

The first step towards consistent LCA modeling is to treat co-production, recycling, and energy recovery by the same allocation procedure. Most guidelines do not consider different modeling methods for different LCA goals and the goal and scope that are represented by the guideline are seldom described in detail. The separation between attributional and consequential LCA is often not consistently performed. While several guidelines consider the cut-off approach and the end-of-life recycling method as direct opposites, these approaches are used in different types of LCA that should not be combined. Instead, the end-of-life recycling approach is directly opposed to the waste mining method – which is only recommended by the ILCD Handbook –, and these methods are combined in the 50/50 method. The market situation of the recycled material indicates which substitution method is applied. If this is not considered, the calculated environmental impacts might not correspond to the actual impacts.

As there is no reference document available yet that gives consistent guidance on allocation for recycling situations, this is the objective of the following chapters of the thesis. In Chapter 5, it is demonstrated that partitioning is not only applicable to co-production, but also to recycling situations. In Chapter 6, a consequential method is developed that facilitates the choice between the three substitution methods, based on the market situation of the material. Further guidance to indicate what material properties are relevant for different applications, how the quality of a material can be quantified, and how market prices could be determined, could be given in PCR and PEFCR documents, as these parameters can be divergent in different sectors.



## Chapter 5: An axiomatic method to identify one's accountability for impacts in Attributional LCA

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### 1. Introduction

The previous chapter demonstrated that scientifically based guidance is missing in current guidelines on how to conduct an attributional LCA in a consistent manner. This results in the fact that several guidelines aim to describe an attributional approach while recommending elements of a consequential LCA study. It was concluded in Chapter 3 that in an attributional LCA, recycling can be modeled by system expansion (the addition of functionalities to the functional unit), partitioning, or the cut-off approach. Several guidelines, however, recommend to model recycling by substitution. For co-production, it is sometimes recommended to apply partitioning, which is consistent with an attributional approach. It seems not widely acknowledged that partitioning can also be applied to recycling situations.

The distinction between product-oriented and process-oriented LCAs was introduced in Chapter 2. In Chapter 3, it appeared that partitioning can be avoided in a process-oriented LCA by applying system expansion. Therefore, this chapter focuses on product-oriented LCAs. The purpose of this chapter is to identify a partitioning approach for recycling situations that provides an answer to the questions that are asked in an attributional LCA. From a set of multifunctionality situations, ground rules – or axioms – are developed that aid in the attribution of impacts among product systems. Based on these axioms, an allocation procedure is identified that best provides answers to a typical attributional LCA goal. This allocation procedure is captured in a set of equations that illustrate the applicability of the procedure to simple cases of recycling, recycling of complex products and co-production.

### 2. Development of axioms to solve multifunctionality situations

In Chapter 2, several descriptions of attributional LCA were introduced. From these descriptions, we concluded that an *attributional LCA aims to assess the accountability for impacts of the subject of the LCA*. The description of the UNEP/SETAC Life Cycle Initiative (2011) was used in the critical review of Chapter 3: *“The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle).”* However, the UNEP/SETAC Life Cycle Initiative does not provide guidance in identifying *how* a burden could be associated with a product. As long as this guidance is missing, it is unclear what is actually calculated by an attributional LCA, and it gives way to all possible modeling choices regarding system boundaries, data types, and allocation procedures. Heijungs (1997) states that *“Answers to the attribution problem can only be given by theoretical reasoning, not by experimental methods; this also means that there is not one unambiguous answer to the question of the attribution of environmental problems to economic activities”*. It is not possible to verify the results of the LCA by measurements: the LCA only calculates potential impacts based on modeling assumptions. It is important to make the models as reliable and robust as possible. Therefore, in this section, we will elucidate our reasoning in the choices that we make to determine the impacts for which the subject of the LCA is accountable.

We are aiming to reason why a product is responsible (or accountable) for certain impacts. In a television broadcast, Richard Feynman has explained the problematics of the “why” question: *“When you explain a “why”, you have to be in a framework that you allow something to be true. [...] You have*

*to know what it is that you're permitted to understand and allow to be understood and known, and what it is you're not<sup>2</sup>* " (The Atlantic 2010).

As the attribution problem – which environmental problems are to be attributed to which economic activities – cannot be solved experimentally, it is necessary to establish an epistemological basis for attributional LCA (Heijungs 1997). Heijungs (1998) proposes to approach this by an axiomatic system. Such a system can be built up by the following elements (Heijungs 1998):

- **“Definitions** state properties which cannot be proven, and which do not imply the existence of the concepts defined.
- **Axioms** state properties which also cannot be proven, but are more than a mere definition, and often presume the existence of the concepts.
- **Theorems** state properties which can (and need to) be proven.”

Axioms are used as elements that are considered to be true, in other words, the moment when we can stop asking “Why?”. Axioms do not necessarily represent absolute truth. In fact, Heijungs argues that the rules on which an allocation procedure could be based are not universally acknowledged and from a scientific viewpoint speculative (Heijungs 1997). It has also been argued that there is not one “true” way to apply allocation; any allocation procedure is an artificial solution to an artificial problem – i.e. dividing a multifunctional process into multiple monofunctional unit processes (Heijungs and Guinée 2007). However, in this chapter, it is not aimed to provide one true solution, but rather a solution that fits the goal definition of the LCA study. The axioms could be used to find a collective agreement on how recycling situations are perceived, or what perspectives could be adopted to stimulate an economy that supports the integration of recycling activities. Therefore, the axioms are open to discussion, which might influence the allocation procedure that is most suitable to represent the LCA goal. The use of axioms facilitates the discussion, as for each axiom it can be identified whether a consensus exists. This enables to build forth on an existing theory while adapting only the axioms on which no consensus is yet established. Furthermore, it could be the case that different types of LCA would require a different set of axioms (Heijungs 1998).

In this section, we aim to build forth on the work of Heijungs (Heijungs 1997; Heijungs 1998), by identifying the appropriate allocation procedure in attributional LCA by an axiomatic system. Axioms are formulated help to identify the processes that require allocation and the products to which these processes are allocated. Also the choice of the partitioning criterion is captured by an axiom.

## 2.1. Allocation procedure

First, it is identified which processes actually require allocation, and which intermediate flows are co-products that can carry environmental burdens. Definitions of the key elements of recycling in LCA were given in Chapters 2 and 3. In Chapter 2, several multifunctionality issues have been introduced: co-production, combined waste treatment, and recycling. A typical configuration of multifunctionality issues in LCA is shown in Figure 5-1. In this section, situations are sketched that represent a different kind of multifunctionality problem. These situations are summarized in Table 5-1. To increase consistency in LCA modeling, multifunctionality situations are as much as possible reduced to a few key elements. If reasoning or argumentation is difficult to apply or to follow in one case study, a

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<sup>2</sup> In response to the question “*Why do magnets repel each other?*” Feynman explains the difficulties of the “why” question. He uses an example of Aunt Minnie who is in the hospital. Why is she in the hospital? Because she went outside, slipped on the ice and broke her hip. This answer can be satisfying if you understand that people who break their hip go to the hospital, and if you understand that ice is slippery. However, you could continue asking the “why” question. Why is ice slippery? This could go on until you reach a statement on which there is a common understanding or agreement.

comparable situation could be sought for to explain the mechanisms in a more intuitive way. The same mechanism can then be applied to the situation under study. In each of the situations described below, it is identified how allocation can be applied in a way that represents the responsibility for impacts of the relevant products in the multifunctional product system. From these situations, definitions and axioms are derived which can be applied to similar situations in divergent case studies. From these axioms an allocation procedure is derived, which can be considered the *theorem*.

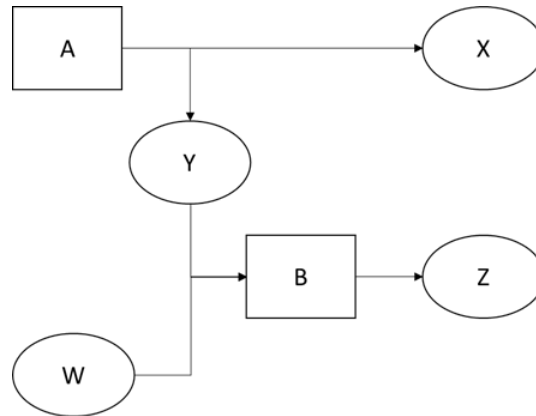


Figure 5-1 Typical configuration of multifunctionality situations in LCA. Example processes and flows are given in Table 5-1

Table 5-1 Example processes and flows for the multifunctionality scheme of Figure 5-1. Blue boxes refer to production processes and red boxes to treatment processes. Yellow boxes are products, gray boxes are wastes and green boxes represent elementary flows

Situation	A	X	Y	W	B	Z
1	Primary production process	Co-product from A	Co-product from A	Product from another product system	Downstream production process	Product from B
2	Primary production process	Product from A	Processing waste from A	Waste from another product system	Waste treatment process for Y and W	Elementary flow from B
3	Primary production process	Co-product from A	Intermediate processing flow from A	Product from another product system	Treatment process of intermediate flow	Co-product from A
4	Primary production process	Co-product from A	By-product from A	Product from another product system	Downstream production process	Product from B
5	Primary production process	First use of product from A	"X" at the end of life	Product from another product system	Waste treatment process for "X" at end of life	Elementary flow
6	Primary production process	First use of product from A	"X" at the end of life	Product from another product system	Recycling process for X	Recycled product from B
7	Primary production process	First use of product from A	"X" at the end of life	Product from another product system	Waste treatment process for "X" at end of life	By-product from B

*Situation 1*

The user of Co-product X and the user of Co-product Y are both responsible for impacts that take place during the co-producing Process A (Figure 5-2). Inputs of intermediate flows in Process A might be influenced by the need to produce both co-products. For example, the production of a co-product can motivate the choice of using one reactant or another. Therefore, all co-products are responsible for the cradle-to-gate impacts of these intermediate flows. Furthermore, intermediate flows that are produced in Process A that are not co-products require waste treatments and should be modeled from gate to grave.

Axiom 1: All co-products are responsible for cradle-to-gate and gate-to-grave impacts of flows that are used and produced during the co-producing activity.

The user of co-product X is not responsible for downstream impacts of Co-product Y. For example, in the production process of bitumen, several co-products are produced: gasoline, kerosene, gas oil and fuel oil (ISO 2012). The user of bitumen (Product X) is generally not considered to be responsible for downstream impacts of gasoline (Product Y), such as transport or the construction of petrol stations (Process B). This is demarcated by system boundaries. If these system boundaries would not exist, the user of bitumen could be held responsible for all worldwide impacts, as on a macro-level all product systems interact with each other.

Axiom 2: The user of a co-product is not responsible for the downstream impacts of other co-products that are produced by the same product system.

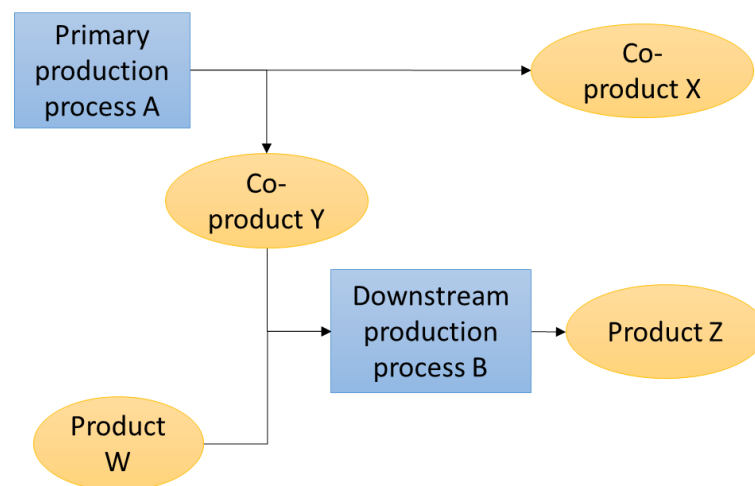


Figure 5-2 Schematic representation of Situation 1

*Situation 2*

Where a production process exists due to the demand for a product with a certain (economic) value, a waste treatment process exists due to the supply of waste with certain physical properties (Figure 5-3). Figure 5-3 is an example of combined waste treatment. Waste treatment process B treats two waste flows: Y and W. Combined waste treatment is not a case of joint production, as the treatment ratio of the two waste flows can in most cases be adjusted. If combined waste treatment takes place, the responsibility for impacts of each waste flow can be reflected by physicochemical causality – i.e. modeling physical relationships. However, there are examples of waste treatment processes that are optimized for specific flow ratios. Therefore, Guinée et al. (2004) recommend applying allocation on a physicochemical basis where possible and economic allocation to the remaining flows, based on the relative revenue provided by the treatment of the waste. The product system that generates a material that requires waste treatment is responsible for the impacts that take place during the treatment process. This follows the “polluter pays” principle, which is implemented as policy in several countries, such as “la responsabilité élargie du producteur” in France (Ministère de l'Environnement de l'Energie et de la Mer 2016). Therefore, in Situation 2, Waste treatment process B is allocated between the waste flows Y and W, which are subsequently modeled in the product systems that supply Y and W, respectively.

Axiom 3: The product system supplying the material that requires waste treatment is responsible for impacts that take place during this treatment

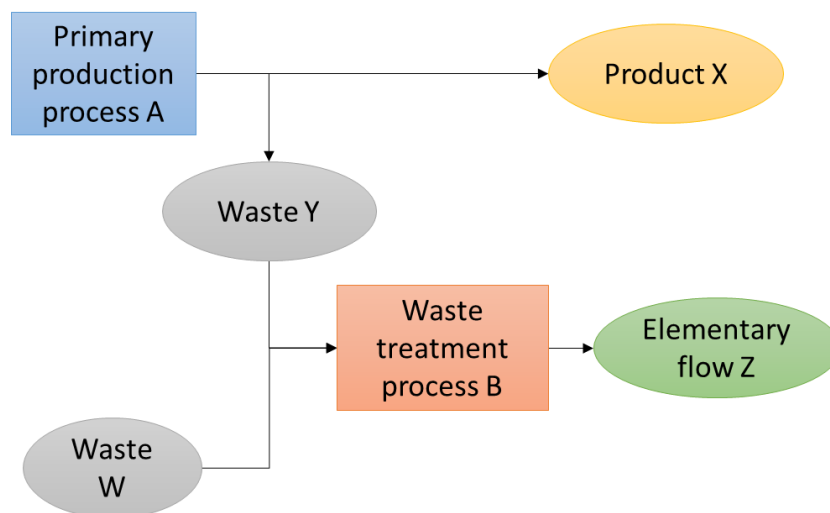


Figure 5-3 Schematic representation of Situation 2



*Situation 3*

In Figure 5-4, Product X is, at least partly, responsible for the impacts of Process A. However, if Intermediate processing flow Y contains waste material generated by A, Product X is responsible for the impacts of Process B as well, based on Axiom 3. Product W could be necessary to transform the waste that was generated by Process A into a valuable Product Z. Product Z is responsible for impacts that take place during Process B, but the inventory of Process A might have been influenced by the foreseen production of Product Z. Therefore, Products X and Z are both responsible for Processes A and B – including the consumption of Product W. Here, the distinction between “intermediate processing flow” and “co-product” is important, as the first might be a synonym for “waste flow” which cannot carry impacts. Weidema et al. (2013) introduce the difference between a “material for treatment” – e.g. a waste flow – and a “co-product”. They define a material for treatment as *“a by-product/waste that no other activity in the same geographical area has as its positive reference product, and which therefore cannot substitute a reference product as an input to an activity”*, where a reference product is *“a product of an activity for which a change in demand will affect the production volume of the activity”*. Weidema et al. (2013) identify the point where a product can be considered to be a valuable co-product at the point where it can substitute a reference product from another production process, i.e. “the point of substitution” (Weidema et al 2013).

Definition 1: A co-product is an intermediate flow that can substitute a reference product from another production process.

In practice, this means the co-product cannot contain traces of waste that are specific to the material source. For example, if a metal can be mined in different regions and one region contains radioactive elements, the metal is considered as a co-product of the other products from the ore from the moment that all radioactive elements are removed from the product.

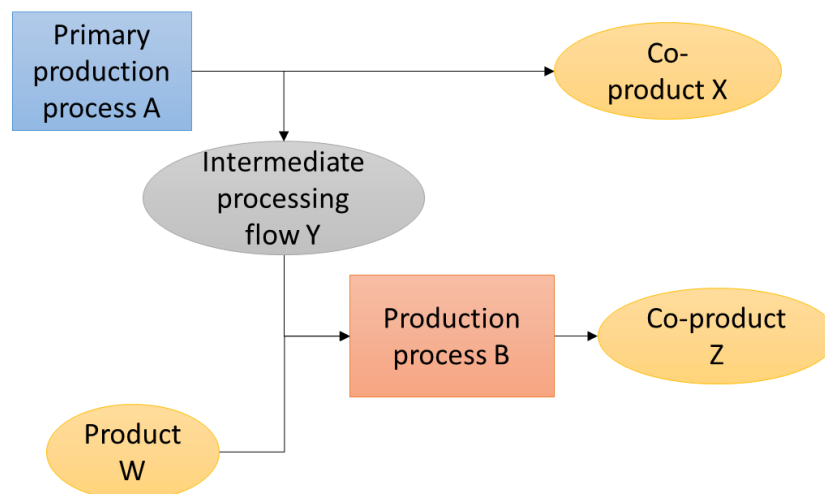


Figure 5-4 Schematic representation of Situation 3

*Situation 4*

By-products could be distinguished from co-products, by the fact that their revenue is not necessary to make the co-producing process economically viable (Gupta and Krishnamurthy 2005). Therefore, by-products are often considered as burden-free outputs. However, the status as “co-product” or “by-product” might change over time with changing market prices. A product that is first considered a by-product might become the main motivator for a production process if the market situation changes.

From Definition 1 it can be concluded that the relative revenue generated by a product is not a criterion to define its status as “co-product”. Combining Definition 1 with Axiom 1 we learn that, if the by-product can substitute a reference product from another production process, this by-product is (partly) responsible for the impacts of the co-producing activity. Therefore, the situation of Figure 5-5 is the considered same as the situation of Figure 5-2.

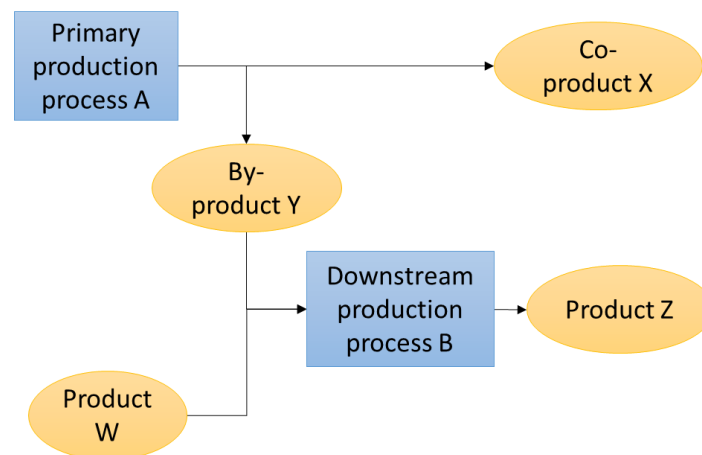


Figure 5-5 Schematic representation of Situation 4

*Situation 5*

Situation 5 is not a multifunctionality situation. However, this situation illustrates the similar structure of a co-producing process and the end-of-life treatment of a product. When the product system under study is not limited to cradle to gate but aims to cover the whole life cycle from cradle to grave, the end of life treatment of Product X must be considered as well (Figure 5-6). “Product X at the end of life” is a “material for treatment” that is supplied by the product system that delivers the 1<sup>st</sup> use of product X, similar to Situation 3. The first user of Product X is responsible for impacts that take place during the waste treatment of “Product X at the end of life”, following Axiom 3.

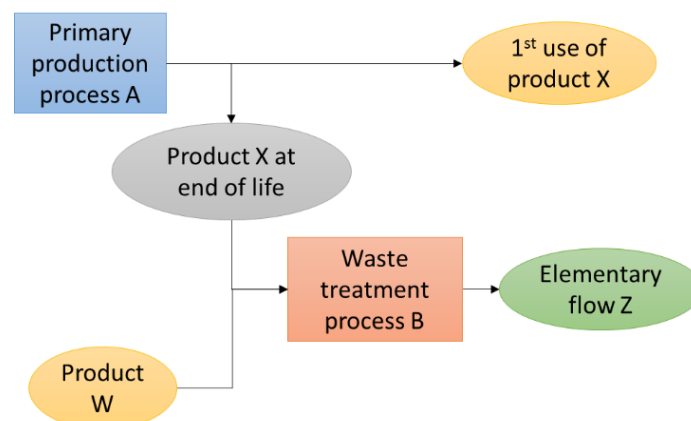


Figure 5-6 Schematic representation of Situation 5

*Situation 6*

Instead of waste treatment, Product X could undergo a recycling process at the end of life (Figure 5-7). The only difference between a waste treatment process and a recycling process is the fact that the latter has at least one useful output (Guinée et al 2004). Therefore, the recycling process is considered to be an alternative waste treatment option.

Definition 2: A recycling process is a treatment process for a material that requires waste treatment, which produces a product as well.

From Axiom 3 and Definition 2 it is concluded that the 1<sup>st</sup> user of Product X is responsible for the impacts that take place during the recycling process. Sometimes it is considered that Recycling process B provides two functions: waste treatment of Product X and production of Product Z. The impacts of Process B are then partitioned between Product X and Product Z, which is illustrated by Guinée et al. (2004). However, it could be argued that Recycled product Z is responsible for impacts that take place during Process A as well. Some materials might be extracted under the assumption that the material will be used multiple times, such as certain metals. High-quality materials might have been chosen in Process A to make Product X more easily recyclable. Therefore, the other users of this material should be partly considered responsible for the impacts of the extraction process. This perspective supports the concept of “design for recycling”, which is an eco-design strategy. Eco-design is an approach that focuses on making more environmentally friendly products (Maris et al 2014). Following this reasoning, Situation 6 becomes comparable to Situation 3: Recycled product Z and the 1<sup>st</sup> use of product X are both co-products of the product system that comprises Production process A and Recycling process B.

From Axiom 3, Definition 1 and Definition 2 it follows that a recycled product is a co-product of the product system that delivers the material for treatment. This is also corresponding to the definitions of ISO 14040, where a product system is a “collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product” and a co-product is “any of two or more products coming from the same unit process or product system”.

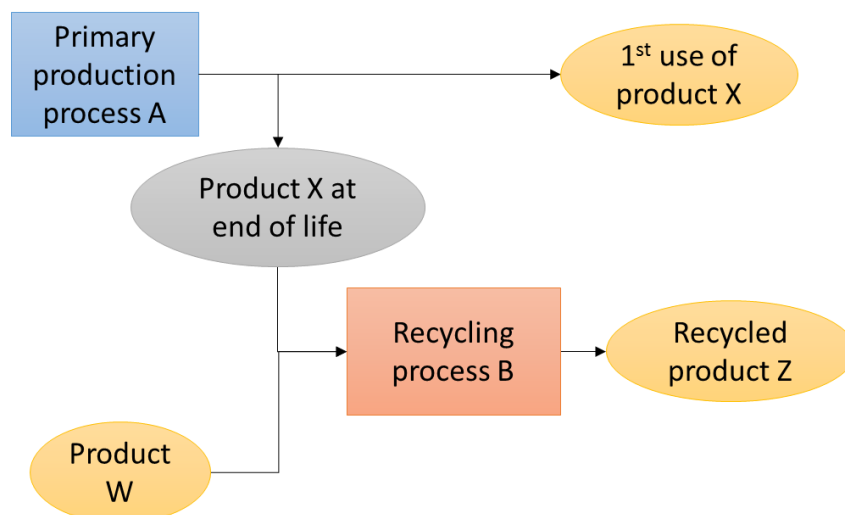


Figure 5-7 Schematic representation of Situation 6

*Situation 7*

Following Axiom 3, Definition 1 and Definition 2, it can be stated that a by-product that is produced during a waste treatment activity must be modeled in a similar way as a recycled product that is supplied by a recycling process. If Product X is, at the end of life, treated as waste, and during this waste treatment a by-product is produced, this by-product should be considered as a co-product of the first use of Product X (Figure 5-8). For example, if a plastic bag is at the end of life incinerated with the recovery of energy, this recovered energy is a co-product of the plastic bag. The plastic bag and the recovered energy are both responsible for the impacts that take place during the production and the incineration of the bag. However, the recovered electricity is also partly responsible for the waste treatment of the bag if part of it is not incinerated but landfilled. This is based on Axiom 1. Although this could seem counter-intuitive, in some cases this waste treatment could be influenced by the fact that the product is also (partly) recycled. For example, a plastic product could be incinerated with energy recovery in Europe. In a hypothetical situation, it might also be collected and transported to Asia, with the purpose to recycle the plastic. Part of the collected plastic might not be suitable for recycling after all, which might now be landfilled in Asia. Furthermore, during the recycling process impurities are removed that will need waste treatment as well. As it is not always clear which impacts belong to “the fraction that is not recycled” and recycling inefficiencies, it is more consistent to treat both types of waste flows similarly.

This perspective enables an optimal configuration of a cascade where a material is used in different life cycles, as described by Ekvall & Tillman (1997). The first life cycle of the cascade system does not necessarily provide the highest revenue. This approach enables to organize an efficient use of materials with a fair distribution of responsibilities for environmental impacts. The primary materials that are extracted in Process A have two potential functions: the use as a physical product – e.g. a bag – and the use of the embedded energy. The fact that the plastic bag must be created first, does not make the bag solely responsible for the impacts of the extraction of primary materials. The impacts of the incineration process are necessary to release the desired energy, although these impacts are highly influenced by the materials that are used to provide the function of the bag, which makes both co-products responsible for these impacts. The responsibility for, for example, a polymerization process can be difficult to accept by the user of the recovered energy. However, this could be explained in terms of “design for recycling” as well: production steps of the bag could be adapted, in order to increase the energy yield at the end of life.

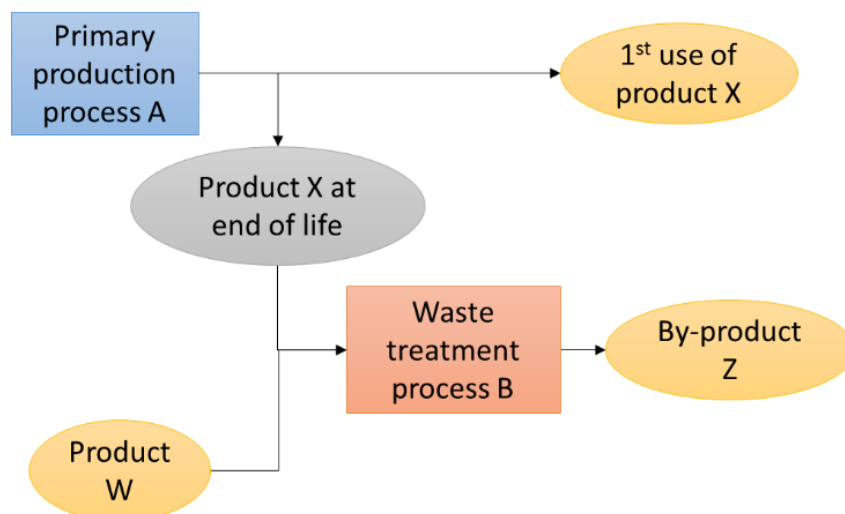


Figure 5-8 Schematic representation of Situation 7

It should be noted that the cascade in Situation 7 is limited to two life cycles, due to Axiom 2. The user of the material in the first life cycle can share impacts with the second life cycle, but not with the third. However, the user of the material in the second life cycle *can* share his burdens with the third life cycle. Therefore, early life cycles will always carry a larger share of the impacts than later life cycles. This is due to the fact that in early life cycles no recycled material is used. As these life cycles depend more on primary materials, they are more accountable for impacts than product systems that use recycled materials.

## 2.2. Partitioning criterion

In Section 2.1 it was determined which processes require allocation and which material flows can be accountable for impacts. Now, it must be decided which criterion is applied to allocate the impacts between the co-products.

From the allocation hierarchy of ISO 14044 (see Chapter 2) it appears that allocation based on physical relationships has the preference over allocation based on other relationships. However, to consider this further, the distinction between combined production and joint production is again relevant – as introduced in Chapter 3. It is acknowledged that allocation in case of combined production should be based on physical relationships, as much as possible. It has even been argued that this is not really a partitioning method, but instead more detailed modeling of what happens (Ekvall and Finnveden 2001). If physical relationships do not provide a basis for allocation, allocation can be based on other relationships. However, for recycled products ISO 14044 proposes a slightly different allocation hierarchy:

*“The allocation procedures for the shared unit processes [for reuse and recycling] should use, as the basis for allocation, if feasible, the following order:*

- physical properties (e.g. mass);*
- economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material; or*
- the number of subsequent uses of the recycled material (see ISO/TR 14049).”*

Therefore, in this section, we discuss the choice between partitioning based on physical properties or economic value in the case of joint production.

### 2.2.1. Representing relative functionality

Whether allocation based on physical properties or economic values should be applied has been extensively reviewed by and discussed in several publications, such as Pelletier and Tyedmers (2011), Ardenne and Cellura (2012) and Pelletier et al. (2014).

There are several physical properties that could be used as the basis for allocation, of which mass might be most often mentioned. To apply allocation, a property must be identified that the co-products have in common, which is preferably relevant for the function of the product (Pelletier et al 2014). For example, in the food sector, Pelletier and Tyedmers (2011) recommend using the caloric value of the co-products as the basis for allocation, as this represents both biophysical and social causality.

However, allocation based on physical properties is often difficult to apply. In the case of open-loop recycling, the recycled material can be of a completely different nature than the primary material. Although the materials might have some physical properties in common, such as mass or energy content, these properties might not be equally relevant for both co-products. In that case, the choice of one property as the basis for allocation could be arbitrary (Werner and Richter 2000).

Furthermore, multiple physical properties might be relevant, which all contribute to the functionality of the product. It could be difficult to identify one allocation factor that captures the difference between the two products on all these properties. In this case, Pelletier et al. (2014) recommend executing several analyses with different allocation factors, to see the relation between environmental impacts and the different functionalities of the product, i.e. a sensitivity analysis. However, we consider that a sensitivity analysis implies that it is not known which property is relevant, while it might be known that multiple properties are actually relevant. A solution could be to apply a weighting procedure on the different properties that contribute to the quality of a material, analogous to the weighting that can be applied to impact categories<sup>3</sup>. This weighting would represent the relative importance of each property to the quality. Based on this weighting, a “single score” could be calculated which represents the quality of the material based on different material properties.

In an ideal world, this single score is represented by the market price of the product. Economic value is the best representative if the market price is based on the intrinsic properties of the material, and all relevant quality parameters are considered in the determination of the price. This has already been suggested by Pelletier et al. (2014) who state that *“Prices represent aggregated proxies for the complex quality attributes inherent to many products and services [...], which cannot be communicated in terms of single physical attributes”*. Also Werner and Richter (2000) argue that *“the market price is considered an expression of the functionality of a certain material quality within a techno-economic system. Relative market prices are therefore a useful parameter to describe the “qualitative” gradation of a material.”* Therefore, we consider that the economic value can serve as a proxy of the functionality of a product.

### 2.2.2. Representing relative responsibility

The market price is sometimes based on properties that are not necessarily related to the functionality of the product. In distorted markets, the market price might not represent the actual value of the product. Guinée et al. (2004) give guidance in collecting price data for products with missing or distorted markets. However, in this thesis, the economic value is considered as more meaningful than merely a “single score” of the product functionality. If one of the recycled materials or co-products has a high quality but suffers from a bad image, the price might be lower than one would expect. In this case, the producer will optimize the production process to have a higher output of products with a high market value, and a lower output of products with a lower value, regardless of the quality. Therefore, one could consider that the relative economic value indicates the relative responsibility for the configuration of the production process, hence its impacts. This could be illustrated by the case of joint mining of iron and rare earth elements (REEs) (which is further discussed in the case study of Chapter 7B). The largest producer of REEs is the Bayan Obo deposit in China. In this deposit, REEs are produced as a by-product from iron. The mining process of the Bayan Obo deposit has been designed to prioritize the extraction of iron (Zhiyi 2012). This has led to mine tailings with high concentrations of REEs, which are difficult to extract. Experts have advised prioritizing the mining activity on the extraction of REEs. This would lead to a more efficient extraction of these elements and lower pollution. As the revenue for iron is sufficient to finance the mining activity, there is no real incentive to redesign the extraction process (Zhiyi 2012). Therefore, the revenue for iron influenced the configuration of the mining activity, which makes the iron ore more responsible for the impacts of mining. To summarize: the relative economic value of a product could indicate the relative

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<sup>3</sup> A similar approach can be applied during the impact assessment. The impact assessment shows the environmental impact considering different impact categories. It can be difficult to make a decision if a product scores better on climate change but worse on acidification than its alternative. By multiplying the results of each impact category with a weighting factor, the results obtain the same unit and can be added up to create a single score (Guinée 2002). The single scores of the two alternatives can now more easily be compared.

functionality of the product, as well as the relative responsibility for the configuration of the co-producing process and its associated impacts.

Axiom 4: The relative responsibility for impacts of each co-product of a multifunctional activity is represented by the relative revenue that the co-product generates.

### 3. Allocation at the point of substitution

The axioms of Sections 2.1 and 2.2 support the following statements:

- Intermediate flows and wastes cannot be responsible for impacts. Further treatment must be modeled by the product system that provides these material flows.
- The product system that produces a waste at the end of life is responsible for the impacts of the recycling process.
- Co-products, by-products and recycled products can be responsible for impacts from the point where they can substitute a reference product from another production activity.

These principles are applied in the allocation procedure that has been introduced by Weidema et al. (2013): “Allocation at the point of substitution” (APOS) (Figure 5-9). This allocation procedure is applied to the “APOS” – previously called “Allocation, ecoinvent default” – system model of the ecoinvent 3 database. In this system model, partitioning is applied between co-products after all necessary treatment steps are modeled up to the point where the co-products could substitute a positive reference flow of another production activity. Allocation is applied based on revenue, unless the revenue does not represent the actual value of the co-products, for example, due to market imperfections (Weidema et al 2013).

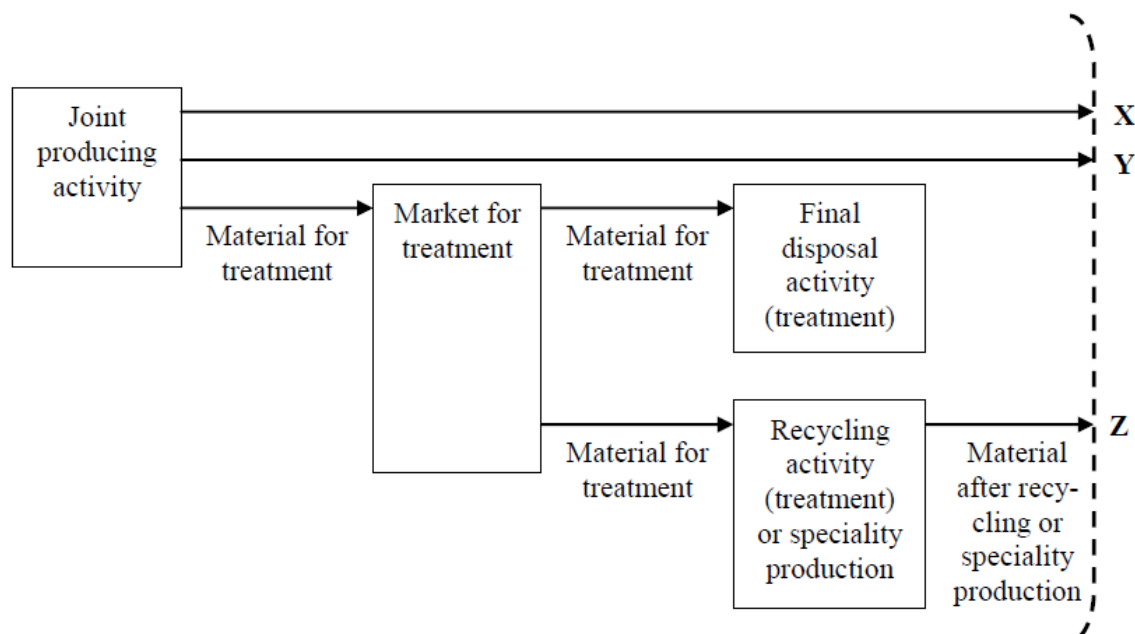


Figure 5-9 Allocation at the point of substitution (Weidema et al 2013)



### 3.1. Step-by-step guidance for APOS

Below, it is demonstrated how APOS can be applied to a multifunctional system. This is done by four steps:

1. Identify the co-products of the production or recycling process
2. Identify the product system that produces the waste
3. Rearrange the system boundaries
4. Apply allocation at the point of substitution

In this chapter, guidance is given to conduct a product-oriented LCA on the demand for a product from a specific production route. The inventory for a product that is supplied by the market can be established by combining all the product-oriented LCAs of the products that contribute to this market. This work is left to database developers and not further discussed in this thesis.

#### *3.1.1. Identify the co-products of the production or recycling process*

The product system under study – here, the foreground subsystem – can contain different unit processes. These unit processes are connected by intermediate flows. It should be determined which of these intermediate flows are considered to be (co-)products, which is the case when the intermediate flow can substitute a reference product from another production activity, i.e. at the point of substitution. Also, for the intermediate flows that are produced by the product system, it should be determined whether they can be considered as co-products, or whether further treatment is needed before an actual co-product is produced. This procedure is represented by Figure 5-10.

#### *3.1.2. Identify the product system that produces the waste*

If one of the material inputs is a waste, it should be determined which product system supplied this waste. From this product system, inventory must be collected on the manufacturing process, waste collection, and waste treatment, as well as on other co-products that were produced by the same product system. If the waste is a product at the end of life, the product system refers to the primary production of this product, and the primary product is one of the co-products produced by the product system.

#### *3.1.3. Rearrange the system boundaries*

Now, the system boundaries will need to be rearranged, such that co-products are outputs of a product system at the point of substitution (Figure 5-11). In this configuration, partitioning can be applied based on the relative revenue generated by the co-products. Prices should represent the relative motivation for the production process. If the replacement rate of the installed capacity is high, short-term prices could be used. If the replacement rate is low, long-term average prices could be better reflecting the motivation of the operation of the process. Price ranges could be used in uncertainty analyses.

#### *3.1.4. Apply "allocation at the point of substitution"*

Allocation at the point of substitution can be applied to the new configuration of product systems. The total revenue of the product system is calculated by (1) multiplying the unitary price of each co-product with the quantity that is produced and (2) adding the revenue generated by each co-product. The allocation factor of a co-product is calculated by dividing the revenue of the co-product by the total revenue of the product system.



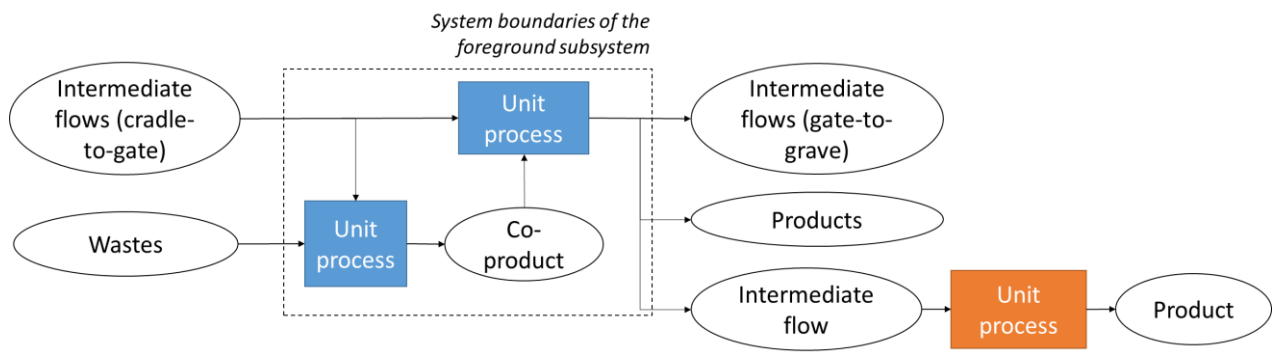


Figure 5-10 Identification of the co-products within the production or recycling process

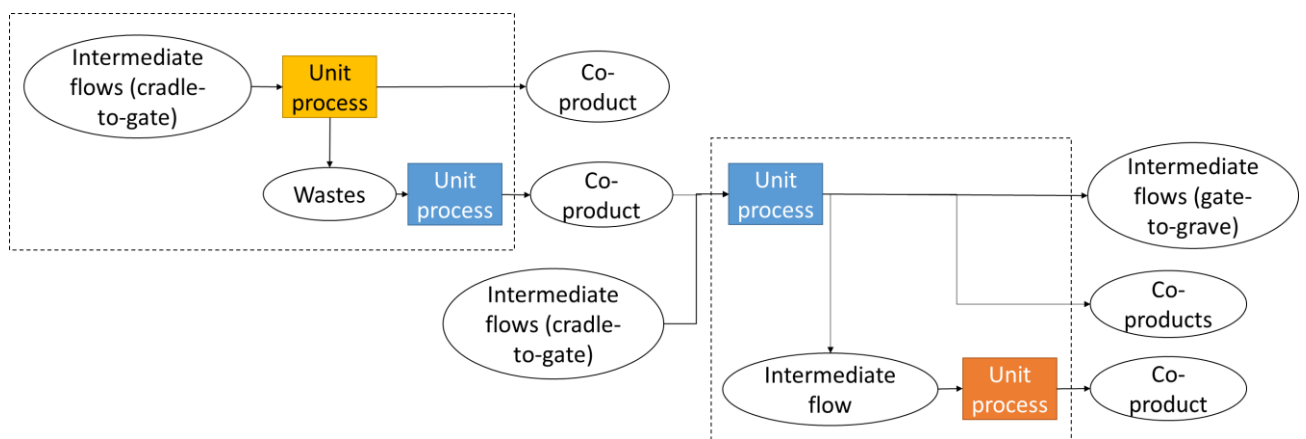


Figure 5-11 Rearrangement of the system boundaries corresponding to the production and consumption of co-products

### 3.2. Analytic approach for APOS

The inventory described above can be implemented in an LCA software, such as Simapro, to calculate the impacts of all co-products. However, the inventory could also be calculated in an analytic manner. The benefit of an analytic approach is that the APOS method can easily be compared to other allocation procedures if they are represented in a similar way. For example, it could be calculated when different allocation procedures provide the same results.

#### 3.2.1. Basic formula for APOS

Allocation at the point of substitution can be represented by Equation E1 and Table 5-2. This equation shows the interactions between the main elements in the product system and was introduced in Chapter 3. Equation E1 represents a simple multifunctional system where the product under study could be (partly) made from recycled materials and could be (partly) recycled at the end of life into one useful co-product. Several elements of the equation must be repeated if more co-products are produced by the product system. The equations contain only elements that are subject to allocation: the co-producing process, the valorization process and the waste treatment of the flows that are not valorized. Distribution and the use phase are not included, as these product stages do not require allocation. The link of Equation E1 with the APOS framework of Figure 5-9 is represented in Figure 5-12.

$$E1. \quad E_{tot} = [E_v + E_d - RC * (E_v - E_{tot(n-1)} * F_{n-1}) - RRE * (E_d - E_r)] * 1/(1 + RRE * C * F)$$

Table 5-2 Legend of terms for Equation E1

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI/unit of analysis
$E_{tot(n-1)}$	LCI attributed to the primary product in the previous life cycle (or in the previous allocation occasion, e.g. if allocation first is applied to the co-products in a cradle-to-factory gate study, and subsequently to the primary and recycled co-product)	LCI/unit of analysis
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI/unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI/unit of analysis
$E_r$	LCI due to the recycling process of the product under study, up to the production of a useful co-product	LCI/unit of analysis
RC	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
RRE	End-of-life recycling rate (recycled or recovered material collected at the end-of-life divided by the available material after the use phase)	$0 \leq \dots \leq 1$
C	Conversion efficiency of the collected material into a valuable product (e.g. (1) from plastic waste (kg) to recycled, ready-to-use polymers (kg), or (2) from plastic waste (kg) to electricity (MJ))	Rate $\geq 0$
F	Relative economic value between the recycled or recovered material or co-product and the primary material (e.g. (€/MJ of electricity) / (€/kg of primary plastic))	Rate $\geq 0$
$F_{n-1}$	Relative economic value between the recycled/recovered material or co-product and the primary material that were produced in the previous life cycle	Rate $\geq 0$

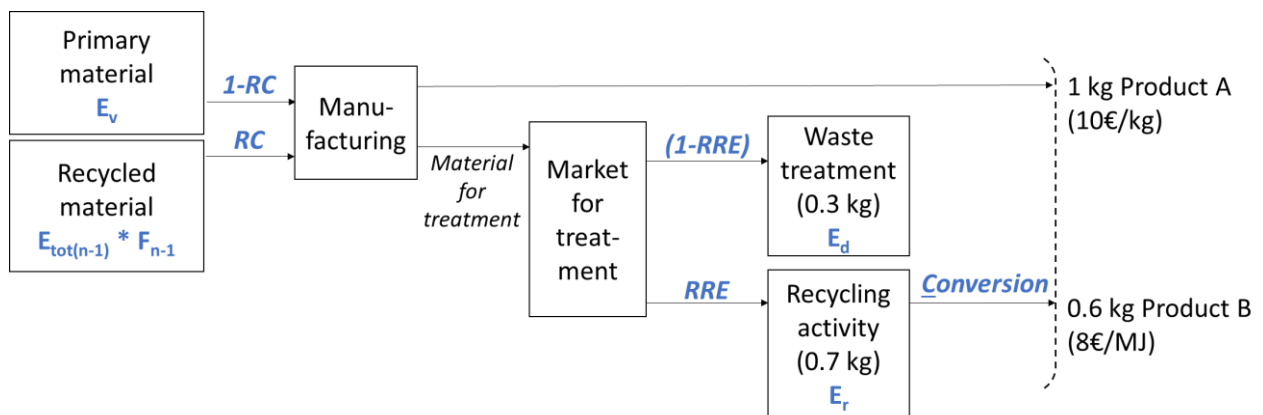


Figure 5-12 Schematic representation of Equation E1 in the APOS framework. In this example  $E_{tot}$  refers to the inventory of 1 kg of Product A,  $RRE = 0.7$ ,  $C = 0.86$  and  $F = 0.8$ . The allocation factors are 67% and 33% for Product A and Product B, respectively

### 3.2.2. Formula for complex products

Equation E1 can directly be applied to a simple product that contains only one material, of which a part is recycled, and which is recycled into only one other material at the end of life. In more complex situations some additional elements are needed. For example, if the product is made from different

types of materials, of which some are partly recycled and some not – or if multiple co-products are produced during different stages of the life cycle. To make the equation applicable to complex products, an extended equation is necessary:

$$E2. \quad E_{tot} = \left[ \sum_{i=1}^n Q_i * E_{v_i} - \sum_{i=1}^n \left( Q_i * RC_i * (E_{v_i} - E_{tot(n-1)_i} * F_{n-1_i}) \right) + \sum_{i=1}^n RI_i * E_{d_i} - \sum_{i=1}^n RI_i * RRE_i * (E_{d_i} - E_{r_i}) \right] * 1 / (1 + \sum_{i=1}^n RI_i * RRE_i * C_i * F_i)$$

Table 5-3 Legend of terms for Equation E2

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the first determining co-product	LCI/unit of analysis
$i$	Refers to an intermediate flow, recycled material or co-product that is used or produced in the life cycle of the first determining co-product	
$Q$	Total quantity of an intermediate flow (recycled plus primary) used per unit of the first determining co-product	Rate $\geq 0$
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI/unit of analysis
$RC$	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
$E_{tot(n-1)}$	LCI attributed to the first determining co-product in the previous life cycle (or in the previous allocation occasion, e.g. if allocation first is applied to the co-products in a cradle-to-factory gate study, and subsequently to the primary and recycled co-product)	LCI/unit of analysis
$RI$	Production rate of the intermediate flow that is (partly) valorized 1) per unit of the first determining co-product or 2) per unit of material entering the valorization process	Rate $\geq 0$
$RRE$	(End-of-life) recycling rate: share of the intermediate flow that is valorized	$0 \leq \dots \leq 1$
$E_d$	LCI due to waste treatment of the fraction of the intermediate flow that is not valorized	LCI/unit of analysis
$E_r$	LCI due to the valorization process of the intermediate flow, up to the production of the determining co-product of the valorization process	LCI/unit of intermediate flow
$C$	Conversion efficiency of the valorization of the intermediate flow into a useful product	Rate $\geq 0$
$F$	Relative economic value between the recycled or recovered material or co-product and the first determining co-product (e.g. (€/MJ of electricity) / (€/kg of primary plastic))	Rate $\geq 0$
$F_{n-1}$	Relative economic value between the recycled/recovered material or co-product and the first determining co-product that were produced in the previous life cycle	Rate $\geq 0$

Figure 5-13 represents how Equation E2 is connected to the APOS framework. In Equation E2, some terms have a slightly different interpretation than in Equation E1. First of all, Figure 5-13 shows that the co-products should be analyzed in a specific order: for each flow, it should be identified which of the co-products that the flow provides is the determining co-product of the process. Although the order of analysis of the co-products is not crucial in an attributional LCA, this is an important step in a consequential LCA. In short, for each process, it should be identified which of the co-products that are produced by the process is the co-product that puts a constraint on the production volume (Weidema et al 2009). This is the determining co-product. Speaking in terms of Figure 5-13, Product B is identified

as the main driver behind the first recycling activity.  $E_v$  refers to the part of the product system that supplies both the first determining co-product and the “material for treatment”.  $E_d$  refers to the treatment process of this material flow if it is not valorized. Valorization refers to any process that enables the extraction of useful materials.  $E_r$  represents the inventory related to the valorization process, and RRE is the share of the “material for treatment” that is being valorized. The conversion factor  $C$  calculates the amount of useful material extracted from the flow of material that enters the valorization process. If multiple co-products are produced during the valorization process,  $C$  is calculated for each of these co-products. The economic factor  $F$  gives the ratio of the market price of the co-product over the market price of the first determining co-product that is represented by  $E_{tot}$  (Product A in Figure 5-13).

It should be noted that  $E_d$ , RRE and  $E_r$  are closely related to each other. Waste treatment is necessary for various intermediate flows that are produced during primary extraction, refining, manufacturing, and the valorization process. However, the waste treatment of these flows are modeled within the life cycle stages in which they take place – i.e. they are part of  $E_v$  and  $E_r$ .  $E_d$  only refers to the waste treatment of flows that are, or could be, also valorized. RRE refers to the fraction of material that does not require waste treatment ( $E_d$ ), but is instead valorized ( $E_r$ ). If during the valorization process a new waste flow is generated that could be valorized as well, another term of  $E_d$  is introduced in the equation with new terms for RRE and  $E_r$  that refer to this specific waste flow. If this waste stream could provide multiple co-products, the determining co-product of the next valorization step should be identified.

#### Complex products and multiple recycling loops

An example of the application of Equation E2 is given in Figure 5-14. This fictitious example depicts the production of a plastic bag. During the manufacturing of the bag, electricity is used of which part is delivered from a municipal solid waste incinerator (MSWI) – this electricity could be considered as “recycled”. At the end of life of the plastic bag, the bag is partly landfilled (30%), and partly incinerated with the recovery of electricity (70%).  $E_{tot}$  refers to the inventory of 1 kg of plastic bags,  $RI = 1$ ,  $RRE = 0.7$ ,  $C = 1.7$  and  $F = 0.2$ . The allocation factors are 81% and 19% for the plastic bag and the recovered electricity, respectively. It could be difficult to identify the inventory that is attributed to the electricity from the MSWI. In fact, in this situation, it could be considered that the electricity can be used in multiple recycling loops. In Chapter 3, an equation was presented that calculates the inventory of a product that uses a recycled material which has been recycled multiple times before:

$$E3. \quad \lim_{n \rightarrow \infty} E_{tot}(n) = b * (a - RC * E_v) / (1 - b * RC * F)$$

- $a = E_v + (1 - RRE) * E_d + RRE * E_r$
- $b = \frac{1}{1 + RRE * C * F}$

This equation can be applied to calculate the inventory of a plastic bag that uses primary polymers, primary electricity (elec) and recovered electricity in the manufacturing stage:

$$E4. \quad \lim_{n \rightarrow \infty} E_{tot}(n) = b * (a - RC * Q_{elec} * E_{v_{elec}}) / (1 - b * RC * Q_{elec} * F)$$

- $a = Q_{polymer} * E_{v_{polymer}} + Q_{elec} * E_{v_{elec}} + RI * (1 - RRE) * E_d + RRE * E_r$
- $b = \frac{1}{1 + RRE * C * F}$

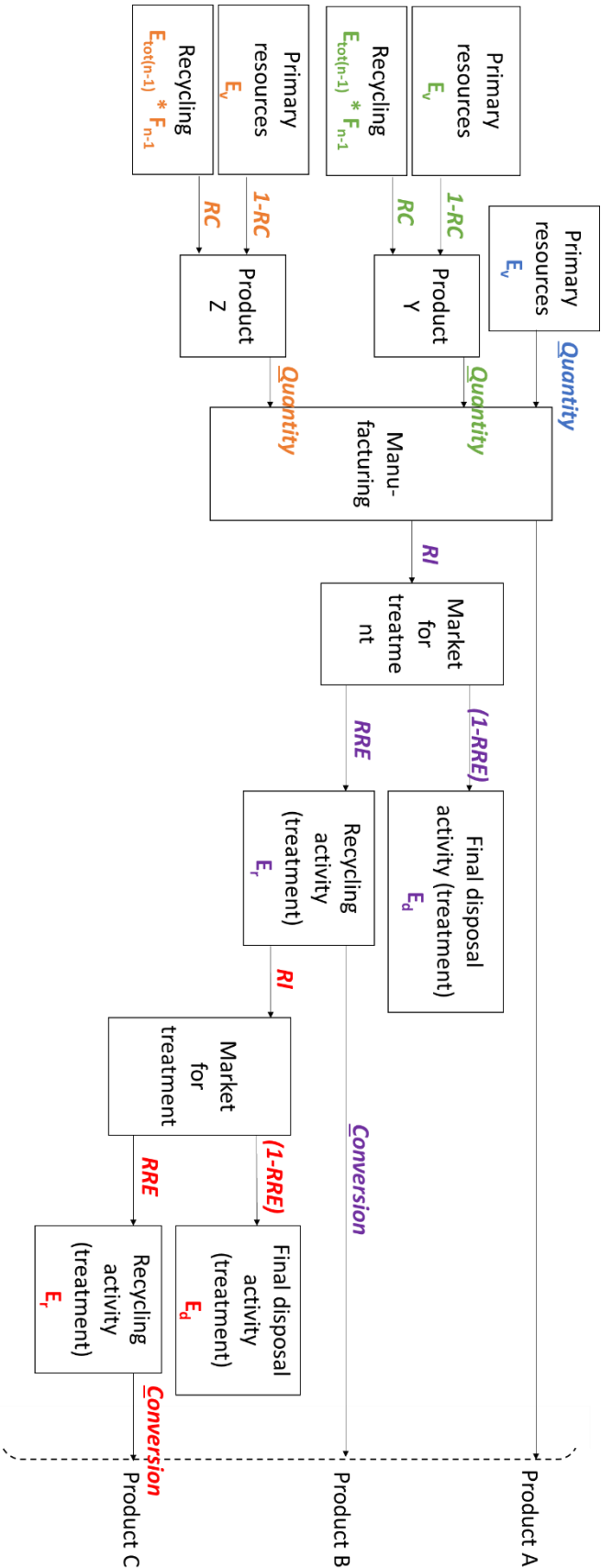


Figure 5-13 Schematic representation of Equation E2 in the APOS framework.  
Flows of different colors refer to flows of different types of materials

It was concluded in Chapter 3 that Equation E4 gives the same results as the end-of-life recycling method when the recycled content and the end-of-life recycling rate are equal. In this situation, this is the case when  $RI * RRE * C = Q * RC$ .

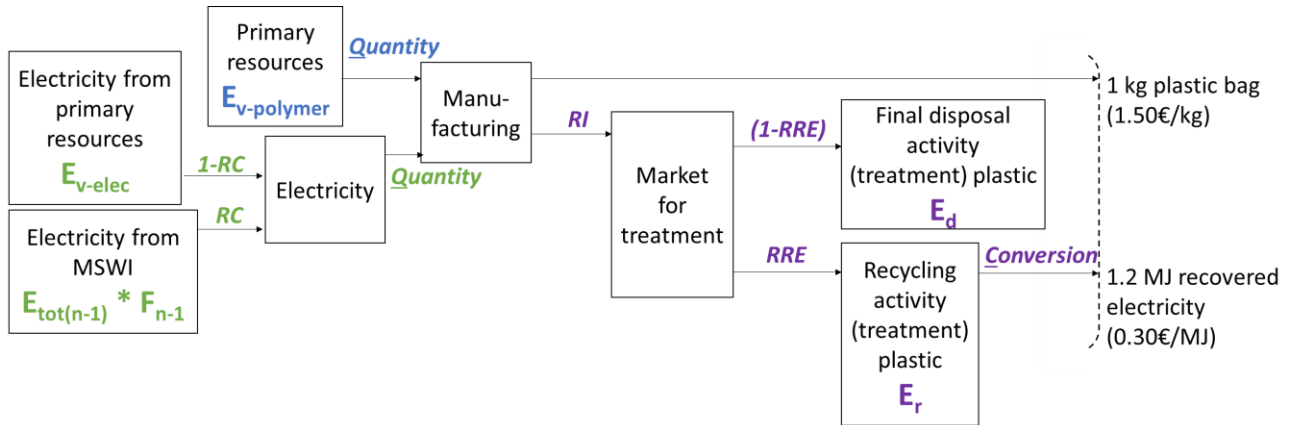


Figure 5-14 Example of the application of Equation E2 to the case of a plastic bag that uses recovered electricity and that is incinerated with the recovery of electricity at the end of life. Flows of different colors refer to flows of different types of materials

### 3.2.3. From a recycling-oriented system to a production-oriented system

Up to now we talked about the “recycled content” and the “end-of-life recycling rate”. In this thesis, it is aimed to provide a consistent approach for recycled materials and co-products. The use and the production of co-products are difficult to capture with vocabulary that refers to recycling. Therefore, the previous equations are expressed in terms of production instead of in terms of recycling.

First, we define the Consumption Rate (CR) of primary material as follows:

$$E5. \quad CR_i = Q_i * (1 - RC_i)$$

And the consumption rate of recycled material:

$$E6. \quad CR_i = Q_i * RC_i$$

There is no longer an explicit difference between primary and recycled materials. Each material should be considered separately, whether it concerns a primary or recycled material or a co-product. Then, we define the Production Rate (PR) of a co-product, relative to the production rate of the product under study (e.g. the first determining co-product):

$$E7. \quad PR_i = RI_i * RRE_i * C_i$$

This production rate can easily be calculated in retrospect, without a full understanding of the configuration of the flows within the product system.

In the previous section, the inventory of the valorization process was defined per unit of to-be-valorized waste<sup>4</sup>. However, this inventory could also be defined per unit of useful output. This can be achieved by the following equation:

<sup>4</sup> A process that is expressed in terms of ingoing waste (i.e. a waste treatment or recycling process) can be modeled as a waste treatment process in Simapro. Alternatively, it can be modeled as a regular production process. In that case, the reference flow of the treatment process can be given a negative sign. If the treatment process is converted into a production process, the reference flow is positive.

$$E8. \quad E_{PR_i} = E_{r_i} / C_i$$

Finally, we could assume that waste treatment of the fraction of an intermediate flow that is not valorized is modeled within the valorization process that produces the intermediate flow. This brings us back to the original equation (E1), with additional terms for the additional co-products:

$$E9. \quad E_{tot} = \left[ \sum_{i=1}^n CR_i * E_{tot(n-1)_i} * F_{(n-1)_i} + RI * E_d - RI * RRE * (E_d - E_r) + \sum_{i=1}^n (PR_i * E_{PR_i}) \right] * 1 / \left( 1 + \sum_{i=1}^n (PR_i * F_i) \right)$$

Note that  $E_{tot(n-1)_i} * F_{(n-1)_i} = E_{v_i}$  if  $CR_i$  refers to a primary product that is the determining product of the primary production process. Therefore, the term  $E_{v_i}$  is omitted from Equation E9. In Equation E9,  $RI$ ,  $RRE$ ,  $E_r$  and  $E_d$  only refer to waste treatment and recycling at the end of life. Other waste treatment of intermediate flows is modeled in the process that supplies the intermediate flow. Therefore,  $E_{tot}$  can refer to a cradle-to-grave analysis if these terms are included, and to a cradle-to-gate analysis if these terms are excluded from the analysis. Equation E9 is schematically represented in Figure 5-15.  $E_{tot}$  can refer to the co-product that is the most logical choice, i.e. the main output of the product system (Product A in Figure 5-15). However, the order of analysis of the co-products, and therefore, the order of the process routes, does not influence the results. It would only influence the terms in which the valorization processes ( $E_{PR_i}$ ) are expressed.

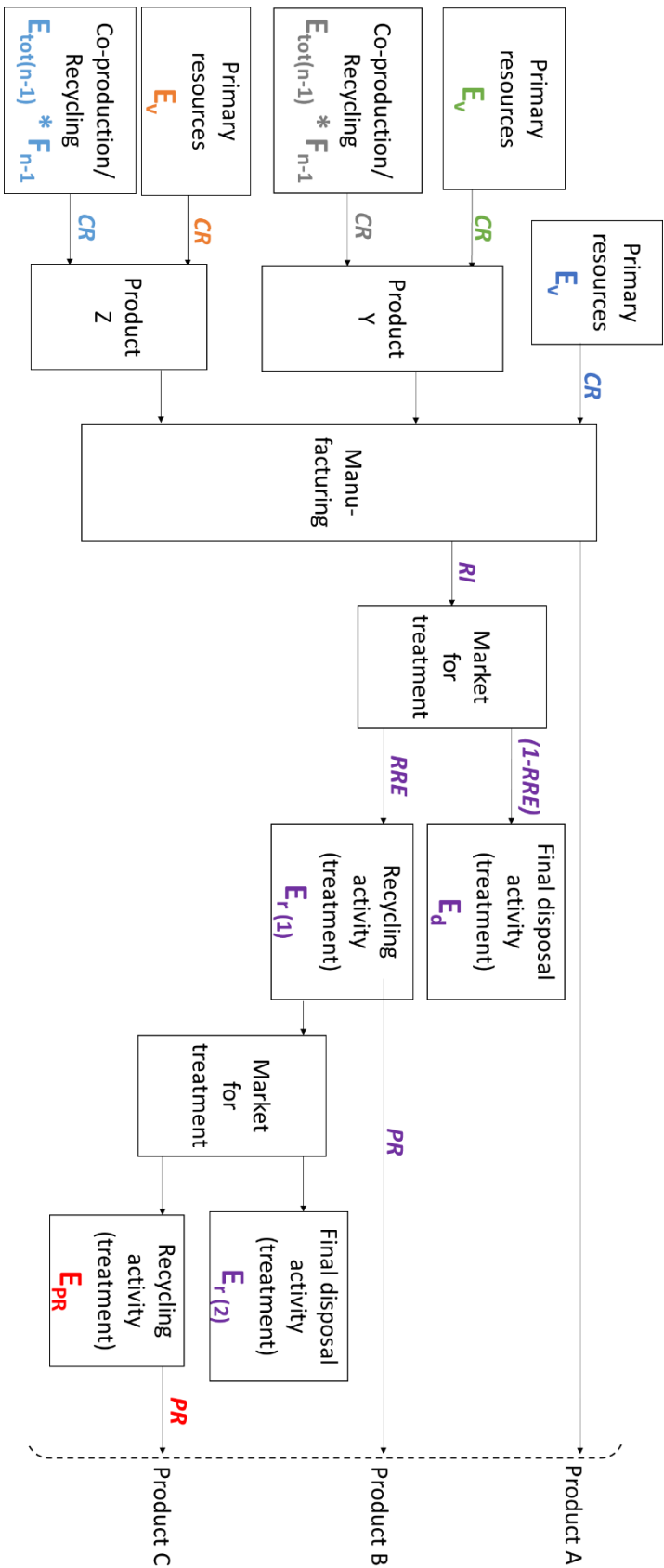


Figure 5-15 Schematic representation of Equation E9 in the APOS framework. Flows of different colors refer to flows of different types of materials. This example represents a cradle-to-cradle study of Product A. During the recycling process of Product A, Product B and Product C are produced. Waste treatment that takes place during and after the recycling process is considered within  $E_r$ .



## 4. Discussion

The allocation procedure that was applied in this chapter is allocation at the point of substitution (APOS). The choice for this allocation procedure was based on an axiomatic system. Therefore, this modeling choice is not considered as a parameter that leads to uncertainty in the results, but it is rather a source of subjectivity. Several drawbacks of the APOS method are discussed, and it is assessed whether the APOS method is compliant with the ISO standards.

### 4.1. Drawbacks of economic allocation

Several drawbacks often brought up by critics of economic allocation. One of these drawbacks is that the user of a cheap, low-impact co-product is unaware of the ecological efficiency of the system that provides the co-product compared to alternative systems that provide the same product (Pelletier et al 2014). However, it was introduced in Chapter 2 that a product-oriented LCA is done with a different purpose than a process-oriented LCA. The eco-efficiency of a production process can be assessed with a process-oriented LCA, which does not require allocation (see Chapter 3).

Another drawback that is often related to economic allocation is the fluctuation of prices. Prices can change between positive and negative values, which would lead to positive and negative impacts attributed to the co-products (Pelletier and Tyedmers 2011). However, allocation is rather based on price ratios than absolute prices. Guinée et al. (2004) and Hischier et al. (2005) argue that price ratios are more likely to be stable than absolute prices. Furthermore, we consider that fluctuating prices could illustrate the usefulness of economic allocation. Prices sometimes indicate whether a product is a co-product, a by-product or a waste (Ardente and Cellura 2012). Wastes cannot carry any burdens (ISO 2006a), which implies that a co-product with a negative market value is burden-free. If allocation is based on physical properties, the moment when this product can be used in an application and it becomes a by-product, the share of burdens attributed to this by-product is dependent on this physical property. This could mean that a small change in economic value could lead to large fluctuations in impacts attributed to the product, for example – following the example of allocation between different types of food – when the by-product has a high caloric value.

Werner and Richter (2000) propose a method for economic allocation for aluminum which is recycled at the end of life. However, they do not apply economic allocation on “new” aluminum scraps. They state that the price of the scraps is not only influenced by the quality of the material, but also by other factors, such as homogeneity and dirtiness. Werner and Richter also see it as a drawback that the prices of new scraps are very dynamic; depending on regional and technological developments (Werner and Richter 2000). They consider a stable price as a precondition to applying economic allocation. This is also stated by Vogtländer et al. (2001). When we need to allocate due to recycling in the far future, it could be difficult that the prices of the recycled material in the future are not known (Vogtländer et al 2001). However, LCAs on products that have a long life cycle bring uncertainties on several aspects. It is not known with certainty that a product is recycled, and which waste treatment or recycling process is applied. The uncertain market price of the recycled material is part of the parameters that would require an uncertainty analysis.

A fluctuating market price does not necessarily make the allocation procedure invalid. The relative market price shows the relative responsibility for impacts at a certain place and time. The market of rare earth elements (REEs) – which is the subject of the case study in Chapter 7 – provides an illustrative example. At this moment, lanthanum has a market price which is much lower than the price of neodymium. Neodymium provides a larger share of the revenue from primary mining than lanthanum. This would make neodymium more responsible for the impacts of the mining process. However, if we find new applications for lanthanum in the future, which creates a shortage of lanthanum, the price

for this element would go up as would the revenue generated by lanthanum. More mining might take place in deposits rich of lanthanum, and the demand for lanthanum carries now a larger responsibility for impacts of these mining activities. A strong fluctuation of prices, such as the case of REO in 2011 (Figure 5-16) requires some extra consideration. The strong price increase of all elements has led to several developments in the markets, such as the opening of new mines and the recovery of REEs from industrial wastes (ERECON 2014). This means that, momentarily, the rare earth elements carried a high responsibility for impacts. However, after the price drop in 2012, several of these initiatives were not economically viable anymore. This was, for example, the case for the Mountain Pass mine in California and the REEs recycling facility of Solvay (GlobeNewswire 2015; Sud Ouest 2016). The duration of the price peak might have been too short to change the production processes in for example the Bayan Obo mine. Therefore, if inventory is used from a specific production route, it might be worthwhile to consider which materials have contributed to investment decisions of the production route. In that case, long-term average prices might be a more reliable indicator for the relative responsibility of a material for the configuration of the production process.

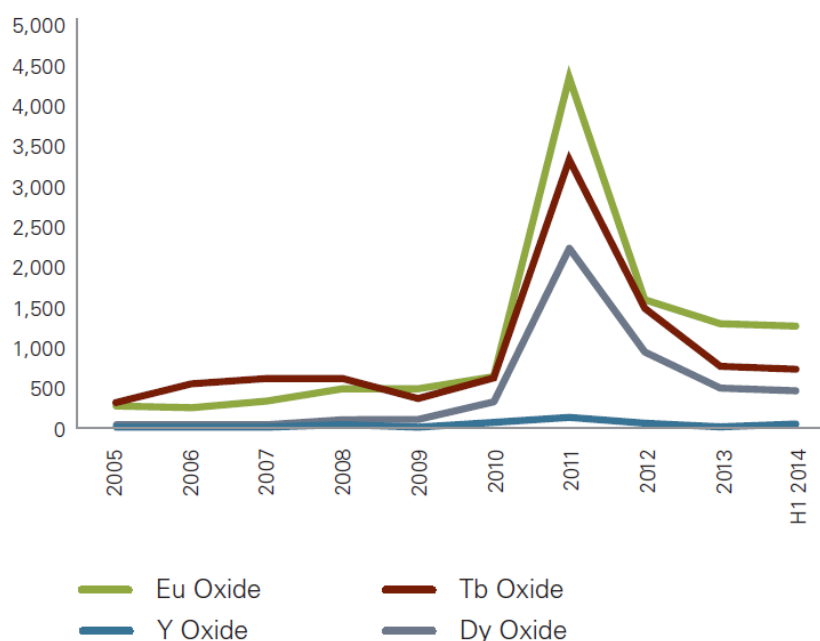


Figure 5-16 FOB prices evolution of a selection of heavy REEs (USD/kg REO) (ERECON 2014)

Also, price fluctuations between different regions could reflect the relative responsibility of impacts of multiple co-products. If the price ratio between two co-products A and B differs between two geographical regions, this could mean that in one country the production is more motivated by the demand for Co-product A while in another country the process is more focused on the production of Co-product B. This influences the relative responsibility for impacts of the two products. However, if the products are traded on the global market, average prices should be used instead. In a background database, data provider could provide representative allocation factors for their production facility. If market mixes are created, such as in ecoinvent 3, average impacts are automatically calculated.

In practice, economic value is one of the widest applied allocation criteria (Pelletier et al 2014). This suggests that it is easier to apply than other criteria and that the results are considered acceptable. Nevertheless, economic allocation is not ideal in all situations. There are products that have an intrinsic value but no market price attributed to them, or that are produced with a different motivation than generating revenue. This could refer to services provided by the government or by volunteers. It might

be possible to identify the value of these products or services in a different way, for example by reduced expenses on health care. This could be identified as their “true value”. ecoinvent already applies “true value” allocation when economic allocation is deemed inappropriate. True value allocation can be applied when the economic value does not represent the functionality of the material and the co-producing activity is not motivated by direct revenues.

#### 4.2. Goal-dependent allocation

Although in this chapter economic allocation is considered the most appropriate allocation procedure, it is acknowledged that different allocations procedures could be suitable in LCAs with different goal definitions. Physical parameters can be applied to maintain a direct link between inputs, outputs, and impacts (Pelletier et al 2014). This is based on the understanding of Pelletier and Tyedmers (2011) that “an attributional LCA aims at isolating and describing the average environmental properties of a product or service life cycle”. Pelletier & Tyedmers (2011) argue that “an overarching objective in the choice of allocation criteria in LCA research should be to produce information that allows us to better understand and manage the environmental implications of the material and energy flows associated with efforts to meet human needs through economic activity”.

Pelletier et al. (2014) discuss that physical allocation reflects best physical causality. This could be useful in an LCA where it is aimed to stay close to “physical realism”. Economic allocation would be suitable in an LCA that aims to represent socio-economic relationships, where impacts are allocated based on “fairness” or with the aim to create incentives for good behavior (Pelletier et al 2014).

We conclude that arguments supporting physical allocation and against economic allocation are based on a different understanding or application of attributional LCA than the application in this chapter, namely to identify for what impacts a product can be held accountable. Therefore, we argue that economic allocation is most useful to represent the relative responsibility for impacts of a co-product. Although physical balances are not kept intact in economic allocation, this is not considered to be the aim of the attributional LCA that is applied here. If the attributional LCA is executed with a different aim than to identify responsibility for impacts, other allocation criteria might be applicable. Frischknecht (2000) states that in certain situations the basis for allocation cannot be identified objectively, therefore, choices for allocation keys are not defensible. This justifies the fact that we included the choice for economic allocation in one of the axioms.

#### 4.3. Subjectivity of axioms

It is possible that one would not agree with some of the definitions or axioms on which the choice for the APOS method is based. Everyone is free to formulate different axioms and develop another allocation procedure based on those (Heijungs 1998). This approach enables to quickly identify on what aspects in the theory disagreement exists, without rejecting the whole procedure due to a disagreement with the interpretation of the results.

Although some axioms or definitions might not be considered “true” by everyone, they help to provide a solution to the allocation problem. For example, some people might not agree with the statement that a recycling process should be considered in the same way as a waste treatment process (Definition 2). However, by assuming this statement to be true, an allocation procedure could be applied. Therefore, the axioms could be interpreted as a list of assumptions that are required to support the method of APOS.

To avoid the freedom of interpretation when a product is a co-product, by-product or recycled product, it was aimed in this thesis to find a single allocation procedure that could be used for each multifunctionality situation. Following a set of rules would lead to more consistency than adapting

each situation to make it intuitively understandable. The development of subjective axioms avoids the need for subjective choices during the assessment and makes the LCA more transparent by making these choices explicit.

#### 4.4. Compliance of APOS with ISO 14044

In this section, we will investigate whether “allocation at the point of substitution” is compliant with the hierarchy of preferred allocation procedures in ISO 14044.

##### 4.4.1. Subdivision

The first solution to avoid allocation that is proposed in ISO 14044 is to apply subdivision, which is referred to as *“dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes”* (ISO 2006a). The main benefit of this approach is that data collection could be limited to processes that are directly related to the co-product under study. Subdivision could be relevant for Situations 3 and 6 of Section 2.1.

In Situation 3, Process A produces two useful outputs: Co-product X and an intermediate flow, from which Co-product Z will be extracted after further processing (Process B). Therefore, it could be argued that Process B is only relevant to produce Co-product Z, and subdivision could be applied between Co-product X and Intermediate flow Y. However, it is possible that the intermediate flow contains waste elements that served the production of Co-product X. Subdivision would, in this hypothetical case, violate Axiom 3. Therefore, following the APOS approach, subdivision is only possible between flows that are both considered to be a co-product according to Definition 1.

In Situation 6, subdivision is often applied between the first and the second life cycle of a product that is recycled, conform to the cut-off approach. This could take place before collection, after collection at the recycling facility, or after the recycling process. This is also recommended by The International EPD® System (2013), and it is in accordance with the method of Guinée et al. (2004), where a recycling process provides the function of waste treatment, as well as the function of the production of a product. However, this approach does not acknowledge that some materials might be extracted with the knowledge that they are used in several life cycles, which makes the recycled product partly responsible for the primary extraction and manufacturing. ISO 14044 states as specific requirements for recycling that *“Reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system”*. Therefore, APOS is considered to be compliant with the requirement to apply subdivision.

##### 4.4.2. System expansion

The second solution to avoid allocation in the ISO 14044 hierarchy is *“expanding the product system to include the additional functions related to the co-products”*. In Chapter 3 it was discussed that system expansion is relevant in a process-oriented LCA. However, system expansion does not provide results on the impacts of individual co-products. Therefore, system expansion would not provide relevant answers to the product-oriented LCA goals. Besides, allocation cannot fully be avoided by system expansion, even in process-oriented LCAs. If the alternative production route that provides the additional function is also multifunctional, allocation must be applied in the background data to avoid endless expansion of the system boundaries due to the addition of multifunctional processes.

##### 4.4.3. Physical relationships

*“Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships*

*between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system"*

It was stated in Chapter 3 and Section 2.2 of this chapter that allocation based on physical relationships is only possible in the case of combined production. Most multifunctionality situations in this thesis refer to situations of joint production, to which this step in the allocation hierarchy is not applicable. However, some cases of combined production exist in this thesis, such as the combined separation of rare earth elements from different deposits in the case study of Chapter 7. Furthermore, in the case study of the recycling of PVC (Annex B), the combined recycling of PVC from different types of products is an example of combined production. These multifunctionality situations are modeled according to physical relationships, rather than partitioned by the APOS method.

#### *4.4.4. Other relationships*

*"Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products"*

In this chapter, APOS had been applied using the economic value of the products. By eliminating the applicability of the previous steps of the ISO hierarchy, it could be argued that APOS is compliant to ISO 14044.

#### *4.4.5. Other requirements of ISO 14044*

*"The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure."*

It is considered that the formulation of axioms in this chapter is a clear description of the allocation procedure.

*"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."*

This requirement is fulfilled in APOS.

*"Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach."*

The aim of this chapter was to use reasoning to choose one allocation procedure and to exclude other procedures. Therefore sensitivity analyses will be limited to options that seem plausible within the same goal and scope of the LCA.

*"The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics."*

With APOS, material balances between input and output are kept intact on a unit process level, but not on a product level. However, Weidema & Schmidt (2010) show that any partitioning procedure breaks physical balances. Only the balances of the property that is used as allocation criterion are maintained. It should be considered whether it is this conservation of physical balances is necessary to provide an answer to the questions asked in the LCA. This could be necessary when one is interested in the material flow of a specific element. However, in this LCA we aimed to identify the accountability for impacts of a process and a product, which does not necessarily require balanced physical flows.

#### 4.4.6. Specific requirements for recycling

The ISO hierarchy applies to co-products as well as to reuse and recycling situations. Therefore, in the discussion above recycling situations have been discussed together with co-production. However, it should be considered whether the specific requirements for recycling are met as well.

*“Changes in the inherent properties of materials shall be taken into account. In addition, particularly for the recovery processes between the original and subsequent product system, the system boundary shall be identified and explained, ensuring that the allocation principles are observed [...]”*

APOS does not distinguish between open-loop and closed-loop recycling: the inherent properties of the materials are not relevant – only their status as co-product and their revenue. In the development of the theory in this chapter, we explained where the system boundaries can be put: at the point when the recycled material can substitute a primary material. This is captured in Definition 1.

*“Reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system”*

Axioms 1 and 3 and Definitions 1 and 2 ensure jointly that the recycled material is, together with the primary material, responsible for impacts that take place during extraction and processing of raw materials, and disposal of products that are produced in the product system. However, final disposal is not considered as an activity that requires allocation. In this thesis, it is calculated for what impacts one function of a product is accountable. If the material becomes available for another function at the end of life, the impacts are modeled from cradle to gate with respect to the recycled material – which could also be considered as “cradle to cradle” of the primary material. It could be argued that the material will require waste treatment, even after providing multiple functions. Final disposal is also mentioned in ISO 14040 as part of the life cycle of a product (ISO 2006b). However, we consider that this waste treatment should be modeled in the product system where it takes place. This is integrated into Axiom 2: the user of a co-product (e.g. the primary product) is not responsible for the downstream impacts of other co-products (e.g. the recycled product) that are produced by the same product system.

*“Reuse and recycling may change the inherent properties of materials in subsequent use”*

This is acknowledged in APOS. The inherent properties of the material do not influence the allocation procedure.

*“Specific care should be taken when defining system boundary with regard to recovery processes”*

As stated above, guidance on how to define the system boundary is given in Axioms 1, 2, 3 and Definitions 1 and 2.

*“Several allocation procedures are applicable for reuse and recycling. The application of some procedures [...] is distinguished in the following to illustrate how the above constraints can be addressed.*

- a) *A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in*



*applicable open-loop product systems may follow an open-loop allocation procedure outlined in b*

- b) An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties"*

The suggestion in statement a) has already been discussed in Chapter 4. The formula for multiple recycling loops that is derived in Chapter 3 and demonstrated in the current chapter can be used in this situation. We showed that open-loop recycling can indeed be modeled as closed-loop recycling if the recycled content is equal to the end-of-life recycling rate. Therefore, this formula is only relevant if recycled material is used as an input in the product system. The general APOS formula can be used in each life cycle, i.e. also the life cycle where the first use of virgin materials takes place. Therefore, we would suggest turning statements a) and b) around: an open-loop allocation procedure can always be applied. If it appears that no changes occur in the inherent properties of the recycled material, *and* the recycled content is equal to the end-of-life recycling rate, this open-loop allocation procedure automatically provides the same results as a closed-loop allocation procedure.

## 5. Conclusions

The aim of this chapter was to identify an allocation procedure that best responds to questions asked in an attributional LCA and to show how this procedure can be applied. It appeared in Chapter 2 that different interpretations of attributional LCA exist in the LCA domain. The interpretation that is applied in this thesis is that "attributional LCA aims to assess the accountability for impacts of the subject of the LCA". This means that the allocation procedure should reflect the degree of responsibility for impacts of the co-products of a multifunctional process. As there is no objective way to identify the allocation procedure, our understanding of "responsibility for impacts" is summarized in a set of definitions and axioms. Based on this set, the allocation procedure "allocation at the point of substitution" (APOS) is identified to provide best an answer to the question for what impacts a product is accountable.

This chapter provides step-by-step guidance for applying allocation at the point of substitution starting from a multifunctional foreground subsystem. An analytic approach for product-oriented LCA had been proposed and demonstrated as well. Formulas are proposed for a simple recycling scenario, recycling of complex products and co-production. This enables to understand the interactions between the products and processes in the product system when APOS is applied. Furthermore, APOS can easily be compared to other allocation procedures, if they are represented in a similar way.

The choice of the allocation procedure has a large influence on the outcome of the LCA. Although it was found that APOS – with the application of economic allocation – is the most suitable procedure to calculate the relative responsibility for impacts of co-products, it is acknowledged that this is not the only procedure that could be valid. A different understanding of "responsibility for impacts" could lead to a different allocation procedure. Also, a different interpretation of what is calculated in an attributional LCA would result in a differently formulated goal definition and could ask for allocation based on physical properties instead of economic values. Even though the APOS method is found to be compliant with the requirements of the ISO standards, it is acknowledged that the axioms on which the method is based are subjective. However, it is not possible to objectively choose an allocation procedure. Formulating these subjective choices in clear statements could lead to increased transparency and reproducibility of LCA studies. The logical derivation of the allocation procedure from these axioms gives the allocation procedure a scientific basis.

The application of APOS is demonstrated by the case study on the recycling of rare earth elements from used fluorescent lamps in Chapter 7 and the case studies in Annex A and Annex B. Chapter 8 discusses further the interpretation of the results from the case studies from an industrial perspective. Also, the choice between process-oriented and a product-oriented and an attributional and consequential LCA are further discussed in Chapter 8.





## Chapter 6: The market-price ratio as a new indicator for demand constraints in Consequential LCA

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### 1. Introduction

In Chapter 3, a framework was developed that connects current allocation procedures to the goal and scope of an LCA. It appeared that the end-of-life recycling method, the waste mining method and the 50/50 method are three substitution methods that can be used to model recycling in a consequential LCA. The choice between these methods is implicitly based on price elasticities:

- The end-of-life recycling method is applied if the supply of a recycled material is fully inelastic
- The waste mining method is applied when the demand for the recycled material is fully inelastic
- The 50/50 method is applied when supply and demand are equally elastic

This type of modeling has been presented by, among others, (Ekvall 2000; Weidema et al 2009; Zink et al 2015). The end-of-life recycling method was found to be a suitable substitution method for aluminum, as the supply of recycled aluminum is constrained by the demand for primary aluminum. The 50/50 method appeared to be applicable to the plastics sector. However, it is not always straightforward to identify the most suitable substitution method in other materials sectors. It is difficult to calculate price elasticities and they do not always represent the level of detail or the time zone that is relevant for the LCA study. Even if simplifying assumptions are done, current methods do not give guidance in identifying the product that is substituted. Therefore, it was argued in Chapter 3 that other indicators – besides price elasticities – are necessary to identify the appropriate substitution method in all recycling situations.

This chapter presents an allocation procedure for consequential LCA that uses the market-price ratio between the recycled and the substituted primary material to reflect relative constraints of supply and demand. The consistency of the consequential methodology is further enhanced by the inclusion of stockpiling, which has not been considered in previous methods. A Causal Loop Diagram is introduced that summarizes the consequences of a changing demand for a product, which can be used to identify the affected processes. The allocation procedure is found to be applicable to all situations of recycling and co-production while taking into consideration the preferences of the metals and plastics sectors. Besides, current modeling methods imply that the recycled materials are traded on the market. Interactions between different actors within the recycling chain that do not take place on the market are taken into account as well. Furthermore, the market-price ratio is considered as a good indicator to identify the substitutability of products and the existence of downstream effects.

### 2. Methodological enhancement with regard to constraints of supply and demand

In consequential LCA, the production volume of a co-producing process is determined by only one co-product: the “determining co-product”. The other co-products follow the production of the determining co-product as “dependent co-products”. In Chapter 3, the difference between a determining co-product and a dependent co-product was explained:

- **Determining co-product:** *“a joint product (a product from joint production) for which a change in demand will affect the production volume of the co-producing unit process”* (Weidema et al 2009)
- **Dependent co-product:** a product from joint production for which a change in demand will *not* affect the production volume of the co-producing unit process

Recycled products are by definition dependent co-products of primary products. Therefore, their supply is inherently constrained. However, the fact that end-of-life products are often treated as waste shows that demand constraints are relevant as well – as there is no demand for each type of waste. The same can be stated about primary co-products that are produced as dependent co-products from primary production routes. For each dependent co-product, it must be identified whether supply constraints or demand constraints are more dominant.

In this section, first, the relevance of stockpiling is discussed. Then, the relevance of supply and demand constraints for materials that are not traded on the market is assessed. Furthermore, we argue whether the same allocation procedure might be applicable to all types of co-production, or whether exceptions might exist, as stated in Chapter 3.

### 2.1. Dependent co-products that are stockpiled

Products for which the demand is constrained stay in the technosphere as “anthropogenic stocks”. Anthropogenic stocks have been identified as a significant material source that has been neglected in common LCA practice (Schneider et al 2011; Johnson et al 2013). Schneider et al. (2011) propose to consider anthropogenic stocks in Life Cycle Impact Assessment by extending the abiotic depletion potential with this material source.

Anthropogenic stocks consist of the following elements (Schneider et al 2011):

- *Employed stock*: Resources that are currently in use
- *Hibernating stock*: Resources that are no longer in use, but are not yet discarded
- *Expended stock*: Resources that are discarded
- *Deposited stock*: Resources that are disposed of, e.g. in landfills
- *Dissipated stock*: Resources that are dispersed in nature

In this thesis, anthropogenic stocks are extended by stockpiles of materials that are produced as a co-product, and which are not taken into use yet. These stockpiles, as well as hibernating stocks, expended stocks and potentially deposited stocks are here considered in the Life Cycle Inventory as sources of materials for which the demand is constrained. In other words, anthropogenic stocks are the “marginal supplier” of products for which the demand is constrained.

Demand constraints are considered to be dominant over supply constraints when the additional supply of a material will not be used. An example of a material for which the demand is constrained is ammonium sulfate. Ammonium sulfate is a co-product of the organic compound caprolactam, which is the precursor to the polymer polyamide 6 (see Annex A). Due to increased production of caprolactam in China since 2010, the supply of ammonium sulfate has increased while the demand did not follow (Harrison 2015). Production capacities are therefore not fully utilized, which inspires some companies to reduce their supply of ammonium sulfate (Zapp et al 2007). The demand for ammonium sulfate could be considered inelastic, which would transform the market-based approach of Ekvall (2000) into the waste mining method of Chapter 3. However, it is unlikely that ammonium sulfate is treated as waste, as it can easily be stored (Zapp et al 2007).

Another example of a product for which the demand can be considered constrained is the rare earth element cerium (Binnemans et al 2013a). Cerium is produced as a co-product of neodymium from primary mining, although the concentration of cerium in the ore is much higher than neodymium. Currently, a small surplus exists of cerium and this surplus is expected to increase in the near future (European Commission 2014a). This is due to the balance problem: the ratio in which REEs are demanded does not correspond to the ratio in which they can be produced (Binnemans et al 2013b). This could be solved if new applications are developed for elements that are currently produced in

excess, such as cerium, praseodymium, and samarium (Binnemans et al 2013b). For some materials, it is easy to identify that demand constraints are more dominant than supply constraints, for example when it is known that surpluses exist. Besides for cerium, praseodymium, and samarium, this is also the case for the REEs lanthanum, gadolinium, erbium, holmium, thulium, ytterbium, and lutetium (European Commission 2014a). However, also these elements are not treated as waste, but they are generally stockpiled.

In Chapter 3 it was stated that demand constraints are only relevant for dependent co-products, due to the fact that a constrained demand for a determining co-product simply results in a decreased production of this product. The production volume of a dependent co-product is always influenced by the demand for the determining co-product. Ammonium sulfate is indeed a dependent co-product from the production of caprolactam, which is confirmed in the case study of Annex A. In the consequential case study of Chapter 7 it is demonstrated that the REEs that are produced in surplus are dependent co-products of other elements. This shows that stockpiling is indeed a relevant element in the inventory of a consequential LCA.

Anthropogenic stocks are the marginal supplier of dependent co-products for which demand is constrained.

## 2.2. Dependent co-products that are not traded on the market

Weidema et al. (2009) mention situations for which their guidance on consequential LCA is not relevant, because the materials are not really traded on the market: *“if a specific group of enterprises are so closely linked in a supply chain that the production volumes of the specific suppliers can be shown to fluctuate with the demand of the specific customers”*. One of the examples for this situation is when *“two or more companies are tied together by tradition, or when a supplier has developed its product to meet specific demands of the customer”* (Weidema et al 2009). If this concerns a dependent co-product, the demand is constrained due to the fact that the demand is limited by a specific customer. This situation is illustrated in Figure 6-1. The production quantity of the to-be-recycled waste is dependent on the demand for “Determining co-product A”, while the consumption quantity of the recycled material is dependent on the demand for “Determining co-product B”. Any additionally supplied material might not be absorbed by Product System B and would require waste treatment. Any increase in demand for the recycled material might not be available and will lead to an additional supply of primary material. Therefore, supply constraints and demand constraints are both important. This situation could be relevant for two companies that operate on the same industrial site and the dependent co-product cannot be easily stored (e.g. heat) or transported (e.g. cheap and heavy or voluminous products).

An example of the latter is given by Kätelhön et al. (2016). In their paper, thermal energy can be provided by rice husk from 5 different regions with different transportation distances, natural gas or wood pellets. If the rice husk is not used, it is burned in the fields. Kätelhön et al. (2016) propose a technology choice model based on factor costs of the alternative technologies. It appears that rice husk from zone 1 is the marginal supplier when it is assumed that there are no supply constraints. If supply constraints are included in the model, rice husk is supplied from two zones that can provide the husk with lower costs than natural gas, and the resulting need for heat is supplied by natural gas. However, rice husk from the three other zones will not be used, as the transport distances makes these routes less economically favorable than natural gas. Therefore, the demand for rice husk is constrained by the transport distance from the field. When both constraints of supply and demand are relevant for a material, it must be identified which of these constraints is more dominant to model the effects of an additional supply of or demand for this material.

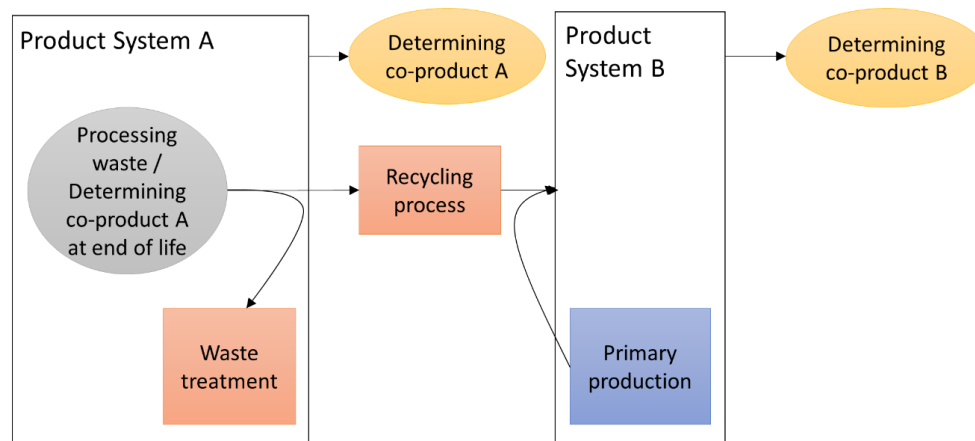


Figure 6-1 Situation in which two companies are connected by the supply and demand of a dependent co-product

Both constraints of supply and demand can be relevant for a dependent co-product that is not traded on the market. Analogous to dependent co-products that are traded on the market, it must be identified which constraints are dominant.

### 2.3. Dependent co-products can substitute a primary product based on functionality

In Chapter 3, it was stated that *“there will be a maximum of one determining co-product from each co-producing unit process”*, unless if one of the co-products does not have an alternative production route (Weidema et al 2009). In this situation, Weidema et al. provide different guidance to model co-production in a consequential LCA. The co-production of rare earth elements (REEs) from primary ore is given as an example for this situation (Weidema et al 2013). In this case, each REE is considered as a determining co-product for which the demand partly leads to increased supply – corresponding to the relative revenue due to this co-product – and partly to a reduced use elsewhere. The result of this type of modeling resembles an economic allocation with the addition of substitution by the marginal user (Weidema et al 2009).

In this thesis, it is considered that each co-product *does* have an alternative production route. Situations are known of co-products that have no alternative primary production route, while they could replace the primary production of a material with the same function. A classic example is the co-production of sodium hydroxide during the production of chlorine. This co-production could displace the primary production of sodium carbonate, which has the same function as sodium hydroxide as a neutralizing agent (Weidema et al 2013). Similarly, for each rare earth element could, in theory, a substitute be identified. This does not necessarily take place on an elemental level, but might be on a technology or system level (Habib 2015; Smith and Eggert 2016). Therefore, the statement *“there will be a maximum of one determining co-product from each co-producing unit process”* is, in this thesis, considered to be true in all co-producing situations.

Habib (2015) described different levels on which substitution can take place: 1) detailed composition level, 2) component level, 3) sub-assembly level and 4) conceptual level. Considering this, Figure 3-11 of Chapter 3 – the simplified connections between different actors in a material market – can be extended by the substitution of applications that provide the same functions (Figure 6-2). If a primary material is demanded for which no production route exists that produces this material as determining co-product (e.g. sodium hydroxide), the supply of this material to “applications using the same materials” is affected. Among these applications, it is the marginal user that will reduce his consumption of the material. According to Weidema et al. (2013), this is the application of neutralizing agent. Sodium hydroxide as neutralized agent is traded on a market of applications that provide the

same function, and it is in this market that a substitute will be identified: sodium carbonate. In consequential LCA, often the *ceteris paribus* assumption is applied, which in this case means that it is assumed that the demand for “neutralizing agent” is not affected by the demand for sodium hydroxide.

“There will be a maximum of one determining co-product from each co-producing unit process.” If there is no alternative production route that produces a dependent co-product as a determining co-product, substitution of the dependent co-product does not take place on a material level but on a functional level.

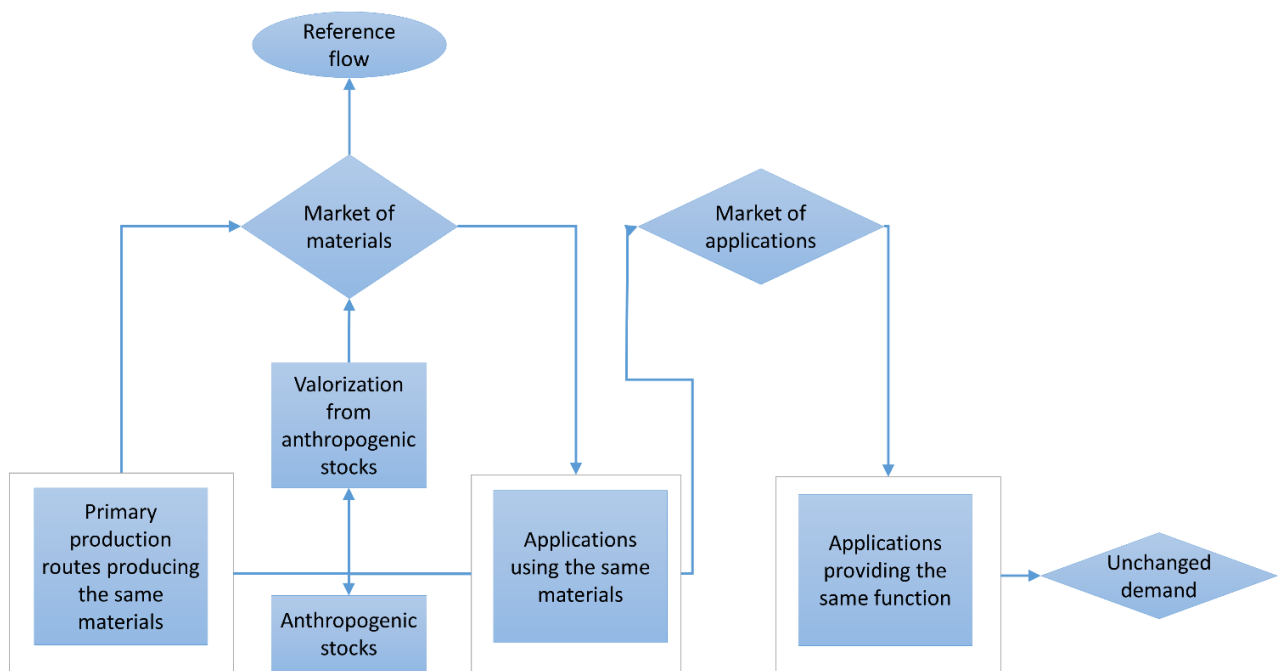


Figure 6-2 Typical connection between different actors and life cycle stages in the material market of the reference flow, extended by substitution among applications providing the same function

### 3. Development of a new indicator for demand constraints

In this chapter, a parameter  $A$  is introduced as a measure for (the lack of) demand constraints. If supply constraints are dominant over demand constraints,  $A = 1$  and the additionally supplied dependent co-product can be used in an application where it could substitute another material. A value of  $A = 1$  corresponds to the market-based approach of Ekvall in which supply is fully inelastic. In this case, processes are modeled according to the end-of-life recycling method of Chapter 3. If the demand is increased for a product for which  $A = 0$ , this product is supplied from anthropogenic stocks: either stockpiling is reduced or waste treatment is avoided and impacts of the valorization activity are modeled. This corresponds to fully inelastic demand in the market-based approach of Ekvall and the waste mining method of Chapter 3. If both supply and demand constraints play a relevant role in the market of a material,  $A$  can have a value between 0 and 1. A value of  $A = 0.5$  is similar to the situation in which the elasticity of supply and demand for a material is equal and will lead to a representation of the 50/50 method of Chapter 3.

The parameter  $A$  is introduced as a new measure for demand constraints. This parameter allows for a continuous substitution method, while representing:

- The waste mining method for  $A = 0$
- The 50/50 method for  $A = 0.5$
- The end-of-life recycling method for  $A = 1$

### 3.1. Determination of $A$

The default value for  $A$  is 0 for a product of which the supply is increased or the demand decreased (a temporary surplus), and 1 for a product of which the supply is decreased or the demand increased (a temporary shortage). This means that in principle any additionally supplied dependent co-product will go to waste treatment or stockpiling, and any additional demand for a product (which is not a determining co-product of a primary production route) will lead to a decreased use elsewhere. Only if it can be argued that the additional supply or demand leads to increased valorization, a different value for  $A$  is valid. Then, the supply of a co-product could lead to the substitution of a primary material and demand can lead to avoided waste treatment or avoided stockpiling.

Dependent co-products have a value of  $A = 1$  if it concerns a primary co-product which is always valorized, for example, the co-product sodium hydroxide that can substitute the production of sodium carbonate (Weidema et al 2013). Dependent co-products have a value of  $A = 0$  if it is a primary co-product and it is known that a surplus exists, such as ammonium sulfate and the REEs that are produced in surplus. In that case, the material is not used and will be stockpiled or it is considered as waste and waste treatment is modeled. It can be more difficult to determine the market situation of a recycled material. Recycled materials can be produced in different material grades, of which some might always be used, while some will always be treated as waste. Therefore, it is important to be able to differentiate between different grades of a material. Price elasticities cannot be used, as these are often aggregated and not situation-specific (Kätelhön et al 2016). Instead, these materials can be differentiated by their market price (Koffler and Florin 2013). Koffler and Florin compare the market price of a recycled material produced by a product system with the price of a primary material used in the same product system, to identify the degree of downcycling. However, Koffler and Florin do not consider that a recycled material might substitute a material from a completely different product category, which however could provide the same function.

The value for the parameter  $A$  for a recycled product is determined by the market-price ratio between the recycled material and the substituted primary material.

We propose to calculate the market-price ratio between the produced recycled product and the substituted primary product in the subsequent life cycle:

$$E1. \quad A = \frac{\text{Market price recycled material}}{\text{Market price primary material}}$$

The market-price ratio could indicate the level of substitutability of the dependent co-product and its substitute. This is especially useful for recycled materials that could be used in the same applications as primary materials, although the material properties are not entirely the same – for example, because the recycled material is of a different grade than the primary material. Furthermore, market-price ratios can be determined for products that are directly traded between two actors in the recycling chain, and between different types of products that provide the same function if substitution does not take place on a material level. Table 6-1 – which is an updated version of Table 3-4 of Chapter 3 – summarizes how  $A$  can be determined for in different market situations of dependent co-products.

The market-price ratio  $A$  between the recycled product and the substituted primary product is used as a representative indicator of the affected process: a high market-price ratio indicates that the market for the recycled product is growing and that the material is of sufficient quality, or there is demand for other reasons, e.g. a “green image”. A low market-price ratio indicates an excess of the recycled material, a low quality or a limited demand due to other reasons, e.g. the materials are not considered to be good substitutes, or a bad image (Bouman et al. 2000; European Commission 2010; Plastics Recyclers Europe 2012). Figure 6-3 indicates the affected process in case of an additional supply of recycled material (i.e. end-of-life recycling rate) and an additional demand (i.e. recycled content) for different values of  $A$ . From Figure 6-3 we can conclude that the end-of-life recycling rate leads to environmental benefits for recycled materials with a market price similar to the avoided primary material. For recycled materials with a market-price below the primary equivalent, the use of recycled material leads to reduced environmental impacts.

Table 6-1 Determination of  $A$  for different market situations of a dependent co-product

		Supply constrained?	Demand constrained?	A-value
Determining co-product		Assumption: supply is unconstrained on the long term	Not relevant: a lacking demand will lead to a decreased supply in the long term	
Dependent co-product	Wastes	Yes	Yes	0
	Primary products that are stockpiled	Yes	Yes	0
	Primary products that are not stockpiled or treated as waste	Yes	No	1
	Recycled products	Yes	Maybe	Market-price ratio

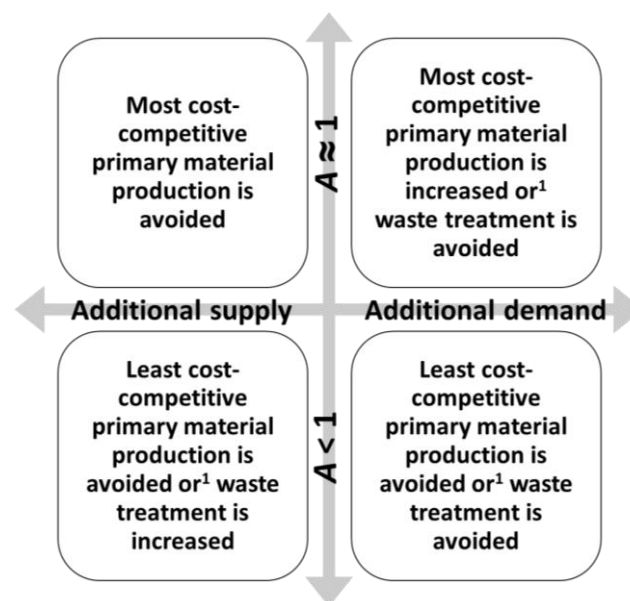


Figure 6-3 Identification of the affected process for additional supply or demand of a recycled material for different market-price ratios. <sup>1</sup> if the material is already (partly) disposed of as waste. Based on Weidema (2001) and the European Commission (2010)



### 3.2. Interpretation of different values for the market-price ratio $A$

When the market-price ratio has a value of  $A = 1$ , the following statements are valid:

- The valorized product and the substituted product are found to be good substitutes
- *And* no extra processing is needed in comparison to the primary equivalent
- *And* no different downstream effects (e.g. during waste treatment) take place due to the use of the recycled material or co-product
- *And* the consumer of the recycled material does not experience any drawbacks that would not take place if primary material were used
- *Or* the source of consumed material is not known, so no conscious choice is made between recycled or primary material

A market-price ratio of  $A < 1$  could indicate the following:

- There is a lack of applications in which the material can be used
- Consumers are limited to a geographical area due to relatively high transportation costs
- Consumers need to invest in machinery or infrastructure, or there are other entry barriers related to use the dependent co-product
- Indirect downstream effects take place (e.g. more refining or processing steps are necessary (Weidema et al 2009), or additional impacts take place during waste treatment (Ekvall and Tillman 1997))
- Applications are limited to a specific market segment, due to (Weidema et al 2009):
  - *“Functionality, related to the main function of the product*
  - *Technical quality, such as stability durability, ease of maintenance*
  - *Additional services rendered during use and disposal*
  - *Aesthetics, such as appearance and design*
  - *Image (of the product or the producer)*
  - *Costs related to purchase, use and disposal*
  - *Specific environmental properties”*

It is very difficult to determine the recycled content of metal products (UNEP 2011). This suggests that the price for recycled metals and primary metals is equal, i.e.  $A = 1$ . This corresponds to the end-of-life recycling method, which is supported by the metals sector (Atherton 2007; Eurofer et al 2013). Plastics often suffer from a bad image. As a result, consumers of recycled plastics are not willing to pay an equal price as for primary plastics (Plastics Recyclers Europe 2012). This automatically leads to a market-price ratio of  $A < 1$ , which confirms the relevance of the 50/50 method for plastics.

Figure 6-4 gives an overview of potential interpretations of different market-price ratios. When the market-price ratio  $A < 1$ , this could indicate that the dependent co-product is not considered to be a good substitute for the determining co-product on which the market-price ratio is based. The existence of demand constraints could be eliminated by finding a better substitute. Also, when the market-price ratio  $A > 1$ , a better substitute could potentially be identified. Two situations are described here that can explain a market-price ratio different than 1.

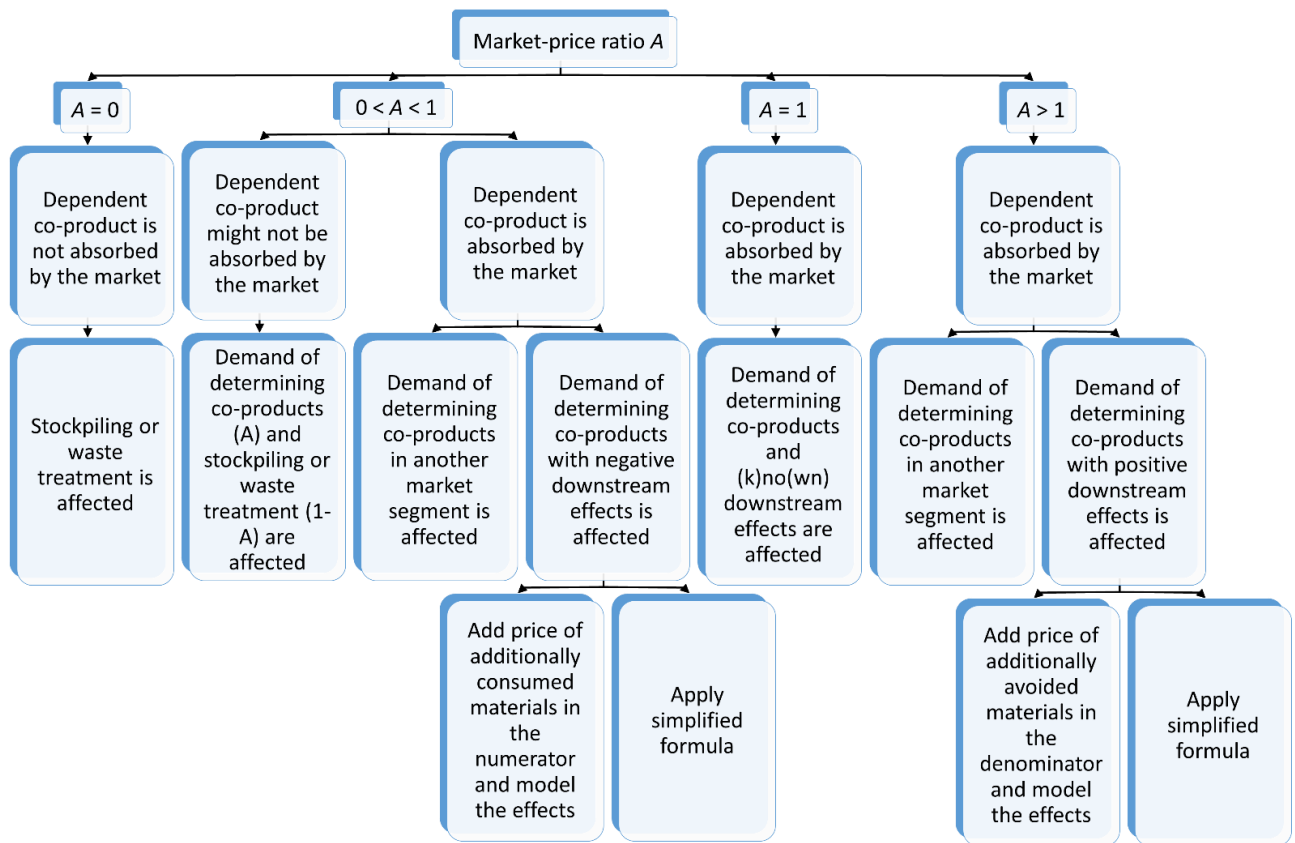


Figure 6-4 Potential interpretations of the market-price ratio A with corresponding modeling procedures

### 3.2.1. Primary material in a different market segment is affected

A market-price ratio lower than 1 could indicate that the material is considered a good substitute in a lower market segment than the one that was initially identified as the marginal supplier. A recycled polymer might not directly compete with a primary polymer of the same type, but rather with a different type of plastic with lower technical properties. A reused leather jacket might not displace the production of a primary leather jacket, but instead the production of a cheaper new jacket of lower quality. It is also possible that the recycled material provides some functionalities that are not provided by the primary material. This could result in a value of  $A > 1$ . It is considered here that, in this case, a closer substitute could be identified as well. A well-defined market segment can help to identify alternative products that are relevant to the market segment, while products from other market segments can be neglected (Weidema et al 2009). However, a better definition of the marginal user does not necessarily result in lower environmental impacts, for example, if the relevant properties of a product refer to immaterial aspects, such as the image of a product.

### 3.2.2. Downstream effects take place

If the market-price ratio is lower than 1, even though there is sufficient demand for the material and the materials are considered to be good substitutes, this could indicate that extra processing steps are needed or that the use of the recycled material leads to different downstream effects in the next life cycle. If indirect downstream effects take place (e.g. increased impacts due to the transport of a heavier product, or a higher impact related to the waste treatment of recycled materials (Ekvall & Tillman, 1997)), the impacts related to these effects should be calculated as well. In ecoinvent 3 this is solved by adding these indirect effects to the inventory of the producer of the material (Weidema et al. 2013). If the use of recycled material leads, for example, to an increased need for electricity in the

subsequent life cycle, these additional electricity costs should be added to the price of the recycled material, as follows:

$$\text{E2. } A = \frac{\text{Market price recycled material} + \Delta_{\text{downstream costs}}}{\text{Market price primary material}}$$

This could make the market-price ratio more close to  $A = 1$ . The additional inventory related to the electricity use should be modeled as well. Similarly, it is possible that  $A > 1$ . However, in this case, the consumer of the recycled material would pay more than he would for primary material. One explanation for this situation could be that the recycled material leads to indirect benefits in the subsequent life cycle. For example, if glass cullet is used in the production process of glass, raw materials can be avoided, but the manufacturing process becomes more efficient as well (GPI 2010). This results in a lower demand for energy during manufacturing. Therefore, the price of glass cullet should not only be compared to the price of the avoided raw materials; the price of the avoided energy should be included in the comparison as well:

$$\text{E3. } A = \frac{\text{Market price recycled material}}{\text{Market price primary material} + \Delta_{\text{downstream costs}}}$$

This avoided energy should also be modeled in the inventory. A simplified formula is proposed in Section 4.2.4 in case this type of inventory is not available.

#### 4. A Causal Loop Diagram to identify the affected processes

The consequences that take place due to the demand for or the supply of products can be summarized in a Causal Loop Diagram (CLD) (Figure 6-5). Causal Loop Diagrams have been used before in the context of consequential LCA to represent specific effects, such as the rate in which a recycled material can displace a primary material (Zink et al 2015). The diagram of Figure 6-5 visualizes all effects that must be taken into consideration in the assessment of an additional demand for a product in general. Positive and negative causal links are represented by pluses and minuses, respectively. A positive causal link, or feedback, means that two variables are changing in the same direction: an increase in one variable leads to an increase in another. A negative causal link represents a change in the opposite direction: an increase in one variable leads to a decrease in another. The variables are explained below.

##### *Demand product*

The functional unit in a c-LCA is often represented by an increasing or decreasing demand for a product. If the product contains different materials, “demand product” represents one of these materials at the time. The consequences of the changing demand of each of the materials in the product are analyzed separately. If a product contains both primary and recycled material, these are considered to be two separate materials that need to be analyzed independently as well.

##### *Downstream effects*

The downstream effects represent all the processes that are modeled in the foreground system, related to the use of a material. For example, if a certain product is used, manufacturing and transport related to this product can take place.

##### *Supply constrained?*

The existence of supply constraints determines the first line of consequences of the changing demand for a product. If the product under study is a determining co-product of a primary production activity, the supply is generally considered unconstrained on the long term, i.e. fully elastic. However, if this is not the case, for example when the product is a dependent co-product, supply is considered constrained, i.e. completely inelastic. It is possible that the supply is partly constrained, which could

be indicated by the price elasticity of supply. In that case, part of the supply is modeled as fully elastic, and part as fully inelastic.

#### *Primary production*

To the extent that supply is elastic, primary production of the marginal supplier is affected.

#### *Supply dependent co-product*

In this diagram, no distinction is needed between co-products, by-products, products recycled at the end of life and wastes. “Supply dependent co-product” refers to any intermediate flow that is produced by a product system that is not the demanded product under study. It is acknowledged that waste treatment activities can provide co-products as well, such as recovered energy. Similarly, during a valorization – or recycling – process, co-products or wastes can also be produced. Of all these materials it should be identified whether the demand for this matter is constrained. “Supply dependent co-product” is analyzed for one intermediate flow at the time: the determining co-product of the following valorization activity.

#### *Demand constrained?*

It should be identified whether the demand is constrained for products of which the supply is (partly) inelastic, as well for the intermediate flows produced by the product system. In the diagram, two different routes are relevant for a changing demand and a changing supply of a product. The degree of demand constraints is indicated by the parameter  $A$ . If supply constraints are dominant over demand constraints,  $A = 1$ . If the demand constraints are dominant over the supply constraints,  $A = 0$ . If both supply constraints and demand constraints play a relevant role,  $A$  can have a value between 0 and 1. This parameter is separately calculated for a changing demand ( $A_{RC}$ ) and a changing supply ( $A_{RRE}$ ) of a material. A changing demand for a product for which the demand is constrained will affect the valorization of materials that are available in anthropogenic stocks. If the demand for this product is not constrained, the use of this material in other product system is affected. A changing supply of a product has the opposite effect: if the demand for this product is constrained, the supplied product will be stockpiled or treated as waste. If the demand is not constrained, the valorization and the use of this product in other applications will be affected. If  $A$  is based on the market-price ratio, the market prices are identified for the determining co-product of the valorization process after valorization and the “alternative product” in the CLD. Guidance to interpret different values for the market-price ratio is given in Figure 6-4.

#### *Anthropogenic stocks*

Anthropogenic stocks are the marginal supplier of dependent co-products for which demand is constrained. If anthropogenic stocks are affected, inventory is modeled related to stockpiling of dependent co-products that are not used yet, as well as the potential waste treatment of hibernating, expended and deposited stocks.

#### *Valorization*

Valorization of a material comprises all activities that take place to make a waste or a co-product a valuable material. This includes sorting and recycling activities, but also evaporation to extract a useful material from a solution, and it could even include the incineration activity that is required for energy recovery (energetic valorization). Valorization can be distinguished from waste treatment if the valorization process differs from the marginal waste treatment activity. The valorization can be represented by actual processes that take place in the foreground system, or by marginal processes if the dependent co-product is traded on the market. If multiple co-products can be extracted during one valorization activity, the determining co-product of the valorization activity must be identified. The other products become the dependent co-products of the valorization process. For example, if an

incineration process produces heat and electricity, heat is either a dependent co-product of the valorization of electricity or vice versa, depending on the situation. Earlier, it was stated that, in general, the consequences of interest in c-LCA are long-term effects that involve investment decisions. This is however not the case for decisions that involve markets with surplus capacity (i.e. when  $A_{RC} = 0$ ). In these markets, short-term effects of small, short-term changes are of interest (Weidema et al 2009).

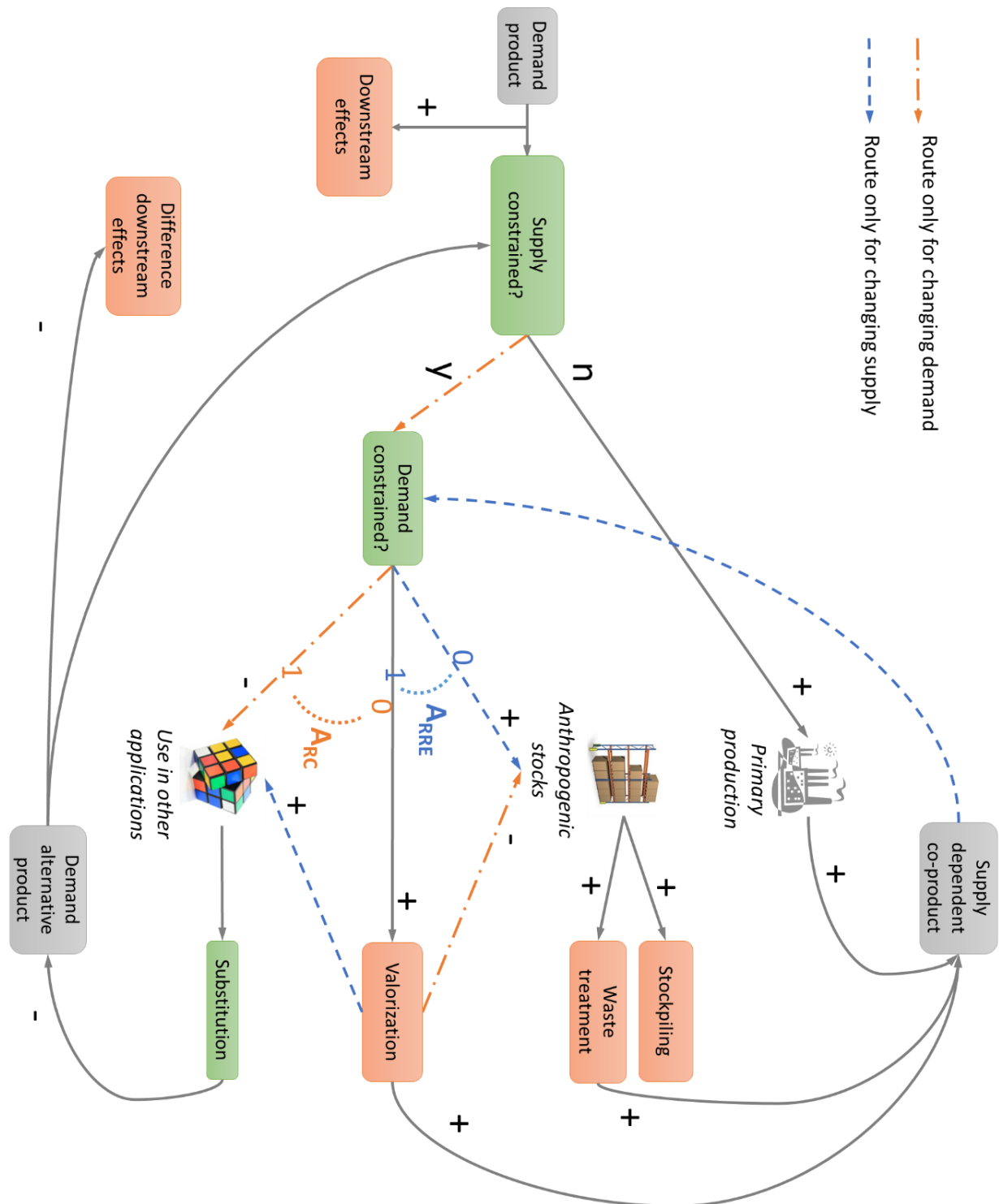


Figure 6-5 Causal Loop Diagram representing the consequences of a changing demand for a product in a multifunctional system

*Use in other applications*

If the demand for a dependent co-product is not constrained, the consequence of an additional demand for this product could be a reduced use of this product in another product system. The product system that is most likely to be affected is the marginal user. This user can most easily substitute the product under study for an alternative material or product that fulfills the same function.

*Demand alternative product*

Substitution can lead to the increased or decreased demand for an alternative product. The market-price ratio between the dependent co-product and the alternative product could indicate whether the products are considered as good substitutes. This could be confirmed by the cross-price elasticities of the materials.

*Difference downstream effects*

Due to the use of a different material, indirect downstream effects could take place. For example, if a recycled material must be used instead of a primary material, more impacts might take place in the subsequent life cycle due to a lower quality of the recycled material. However, the material that is increasingly used in the alternative product system might also lead to benefits in the subsequent life cycle. These effects must be modeled in the LCI as well (Weidema et al 2009; Weidema et al 2013). If substitution does not take place on an elemental level, but on a product or technology level, differences in technology efficiencies and system design must be considered as well.

**4.1. Step-by-step application of the Causal Loop Diagram**

The CLD of Figure 6-5 indicates the consequences that could take place due to a changing demand for a product in a product-oriented LCA, or due to a changing production, valorization or treatment in a process-oriented LCA. Any variable can be the starting point of the CLD. From the starting point, only the outgoing arrows that do not represent the functional unit are included in the analysis.

A process-oriented consequential LCA aims to calculate the impacts caused by the production, recycling or treatment process of the determining co-product. The recycling – or valorization – process of the CLD has three outgoing arrows. All outgoing arrows should be followed – as it is not known whether it is the supply or demand that triggers the valorization process – with the exception of the arrow that represents the functional unit. This means that if “the treatment of [ingoing flow]” is the functional unit, avoided waste treatment is not modeled. If “the production of [outgoing flow]” is the functional unit, the increased use in other applications of this product is not modeled. System expansion – the addition of functions in the functional unit – can reduce the number of effects that is modeled. Any intermediate products that are used in the process are modeled as an “increased demand product” and any outgoing intermediate flow is modeled as “increased supply dependent co-product”. For each intermediate flow, the consequences of this changing demand or supply are analyzed with the CLD.

The modeling principles for a product-oriented LCA are the same as for a process-oriented LCA. However, where a process-oriented LCA uses a process in the CLD as the starting point, in a product-oriented LCA this is the demand for a product. In this thesis, it is generally assumed that the supply of a determining co-product is unconstrained. This means that the additional demand for this product will lead to an additional supply. If the changing demand is analyzed for a recycled material – which is by definition a dependent co-product –, supply is constrained and subsequently, the existence of demand constraints should be identified. This determines which consequences take place due to an increased demand for the recycled product. If the demand is increased for a product that is recycled at the end of life, the end-of-life product is considered as “dependent co-product” which is supplied as a consequence of the increased demand for the primary product.

Figure 6-6 and Figure 6-7 summarize the steps that are taken when the initial starting point of the analysis is a process and a product, respectively. In practice, both types of analyses will be required in an LCA. For example, in the first step of the process-oriented LCA (*“Model the process up to the production of the functional unit or the determining co-product”* in Figure 6-6) it is highly probable that intermediate products are used within the process. The consequences of the increased demand for these products can be analyzed following the steps of Figure 6-7. The steps in these figures are based on the assumptions in this thesis on the full elasticity of supply of a determining co-product and fully inelastic supply of a dependent co-product. The CLD provides a more broadly applicable framework.

A Causal Loop Diagram is presented as a tool to identify the affected processes due to a changing demand for a product, or a changing production of a process.

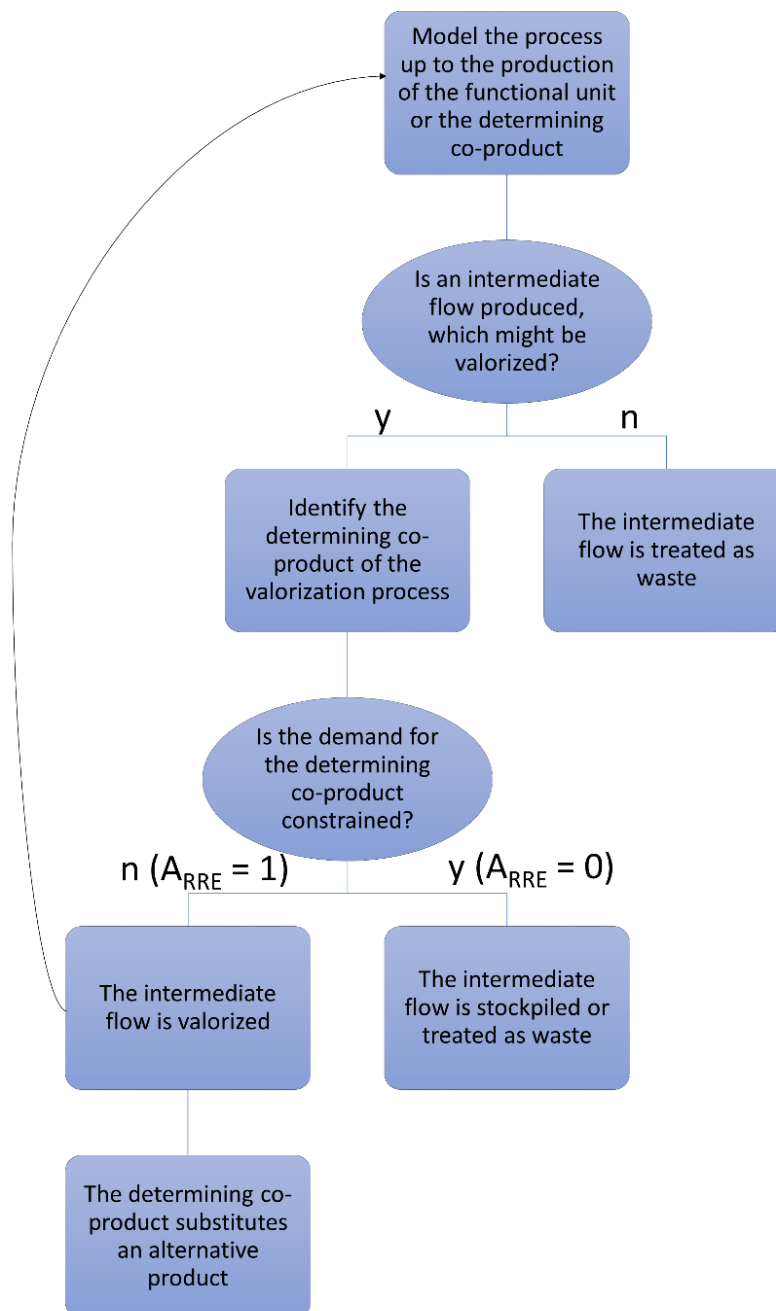


Figure 6-6 Step-by-step guidance to identify the consequences of the operation of a process



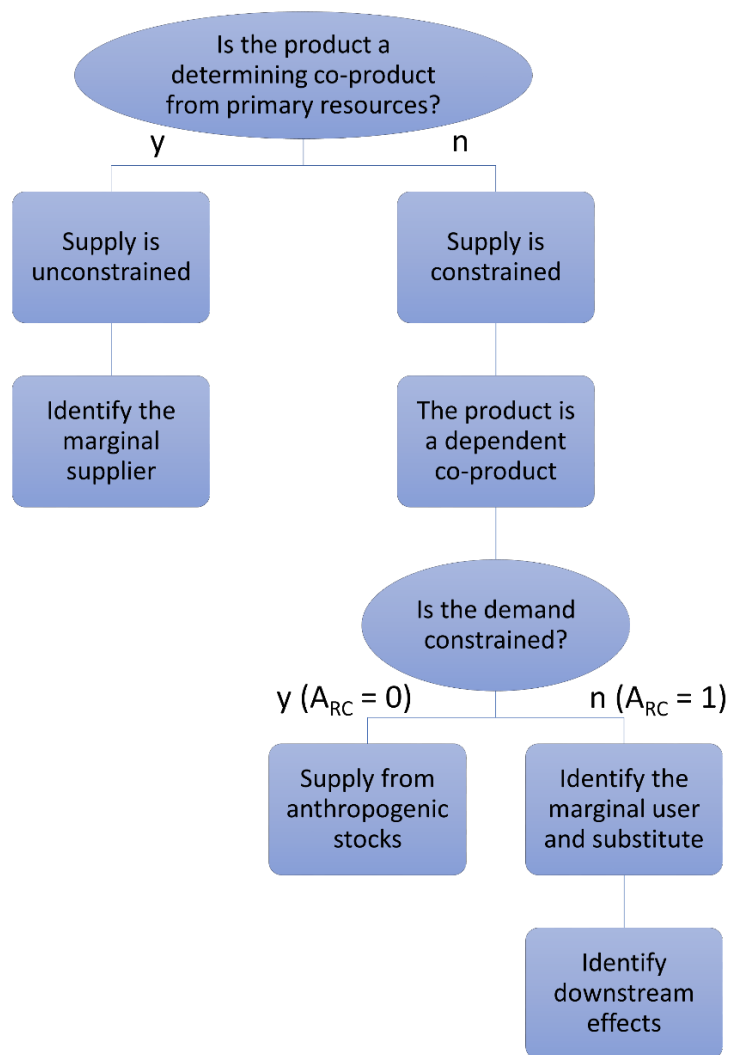


Figure 6-7 Step-by-step guidance to identify the consequences of the demand for a product

## 4.2. The market-driven substitution method

The effects described in the CLD (Figure 6-5) can be represented by a formula in *the market-driven substitution method* that calculates the inventory caused by the demand for a product. First, we show the basic equation in the same style as the equations of Chapter 3. Then, it is shown how this equation can be applied to complex products, and finally, it is slightly rewritten to show a production perspective instead of a recycling perspective. A simplified approach is provided as well, which could be applied in case the market-price ratio is  $A \neq 1$ , while the products are good substitutes, there are no demand constraints and no data is available with regard to downstream effects.

### 4.2.1. Basic formula for the market-driven substitution method

Equation E4 shows the inventory of a material that contains partly recycled material and which is at the end of life partly valorized in recycled material as well. The terms of the equation refer to elements in the CLD, as shown in Figure 6-9. Figure 6-9 focuses only on the consequences due the increased use and production of recycled material. A more general representation that also includes the consumption of primary materials and waste treatment is given in the next section. Equation E4 can be represented in a similar scheme as the formulas of Chapter 3, which is shown in Figure 6-8.



$$\begin{aligned}
 \text{E4. } E_{\text{tot}} = & E_{\alpha} + (1 - RC) * E_v + RC * \left( \frac{(1 - A_{RC})}{C_{RC}} * (E_{RC} - E_d^*) + A_{RC} * \frac{Q_{RC}}{Q_v} * (E_v - \right. \\
 & \left. \Delta E_{\alpha}) \right) + (1 - RRE) * E_d + RRE * \left( (1 - A_{RRE}) * E_d + A_{RRE} * \left( E_{RRE} + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * \right. \right. \\
 & \left. \left. (\Delta E_{\alpha}^* - E_v^*) \right) \right)
 \end{aligned}$$

Table 6-2 Legend of terms for Equation E4

Term	Explanation	Value
$E_{\text{tot}}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI / unit of analysis
$E_{\alpha}$	LCI due to the downstream processes related to the use of the material in the functional unit	LCI / unit of analysis
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{RC}$	LCI due to the recycling process related to the recycled content (including LCI of material losses during the recycling process)	LCI / unit of input material
$E_{RRE}$	LCI due to the recycling process related to the recycled material produced at the end of life (including LCI of material losses during the recycling process)	LCI / unit of input material
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the life cycle under study	LCI / unit of displaced primary material
$\Delta E_{\alpha}^*$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the subsequent life cycle	LCI / unit of displaced primary material
$RC$	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
$RRE$	End-of-life recycling rate (recycled or recovered material collected at the end-of-life divided by the available material after the use phase)	$0 \leq \dots \leq 1$
$C_{RC}$	Conversion efficiency of the recycling process related to the recycled content	Unit of useful output / unit of input material

Term	Explanation	Value
$C_{RRE}$	Conversion efficiency of the recycling process related to the end-of-life recycling rate	Unit of useful output / unit of input material
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$Q_{RRE}/Q_v^*$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RC}/Q_v)^{-1}$
$A_{RRE}$	Market-price ratio between the recycled material and the displaced primary material in the subsequent life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RRE}/Q_v^*)^{-1}$

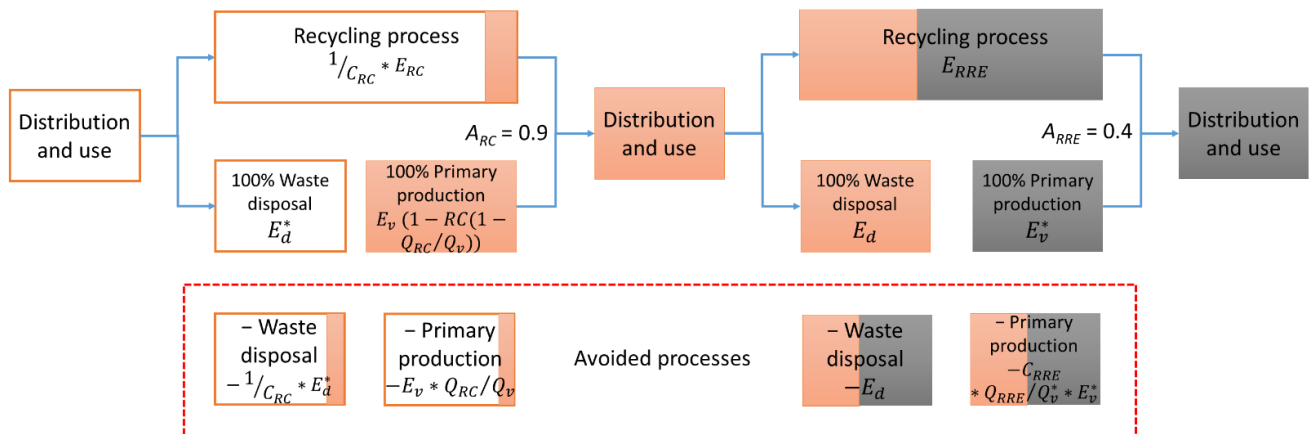


Figure 6-8 Representation of Equation E4 in the style of the formulas and schemes of Chapter 3. Note that in the current chapter some elements are added to the equation that increases the consistency of the approach, such as (indirect) downstream effects

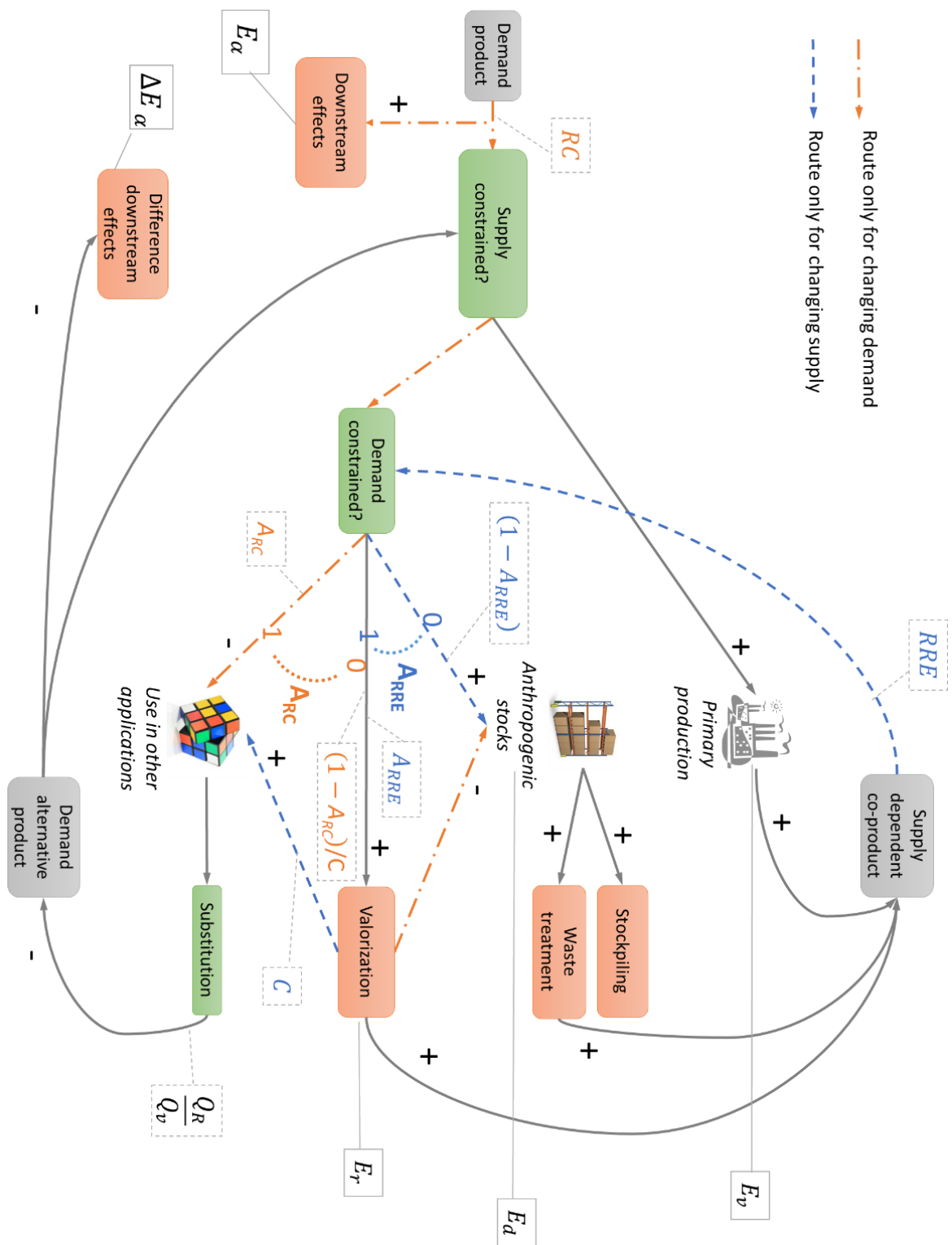


Figure 6-9 Causal Loop Diagram representing the consumption and the production of recycled materials according to Equation E4. The term  $E_r$  in the CLD refers to either  $E_{RC}$  or  $E_{RRE}$  in Equation E4. Similarly,  $Q_R/Q_v$  could refer to either of the quality-correction factors and  $E_v$  of the CLD can represent  $E_v$  and  $E_v^*$  in Equation E4

#### 4.2.2. Formula for complex products

The CLD of Figure 6-9 only shows the effects of the terms that refer to the recycled content and the end-of-life recycling rate. Also, Equation E4 represents a very simple situation with 1 material, 1 recycled content and 1 end-of-life recycling rate. In complex products, several materials exist of which some are recycled, and several co-products can be produced. Also at the end of life, multiple different materials could be considered as a recycled product. Therefore, more guidance is needed on how to apply the equation and the CLD to complex products.

Equation E4 can be generalized to include all material inputs and outputs of the product. This is represented in Equation E5 and the CLD in Figure 6-10. However, it should be noted that Equation E5 is a simplified version of the effects that are modeled in Figure 6-10. Below, it is first shown what effects actually take place, and what assumptions can be done to reach Equation E5. In the example in this section, it is assumed that the market-price ratio  $A$  represents the relevance of both supply constraints and demand constraints, i.e.  $0 < A < 1$ . Hence, the additionally supplied recycled material might not be absorbed by the market.

$$\begin{aligned}
 \text{E5. } E_{tot} = & \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{(1 - A_{RC_i})}{C_{RC_i}} * \right. \\
 & \left. (E_{RC_i} - E_{d_i}^*) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \\
 & \sum_{i=1}^n RI_i * RRE_i * \left( (1 - A_{RRE_i}) * E_{d_i} + A_{RRE_i} * \left( E_{RRE_i} + C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * (\Delta E_{\alpha_i}^* - E_{v_i}^*) \right) \right)
 \end{aligned}$$

Table 6-3 Legend of terms for Equation E5

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI / unit of analysis
$i$	Refers to an intermediate flow, recycled material or co-product that is used or produced in the life cycle of the product under study	
$Q$	Total quantity of an intermediate flow (recycled plus primary) used per unit of the product under study	Rate $\geq 0$
$RI$	Production rate of the intermediate flow that is (partly) valorized 1) per unit of the product under study or 2) per unit of material entering the valorization process	Rate $\geq 0$
$E_{\alpha}$	LCI due to the downstream impacts related to the use of the material in the functional unit	$E_{\alpha_v} + \Delta E_{\alpha}$
$E_{\alpha_v}$	LCI due to the downstream impacts if only primary material were used	LCI / unit of analysis
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the life cycle under study	LCI / unit of displaced primary material
$\Delta E_{\alpha}^*$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the subsequent life cycle	LCI / unit of displaced primary material

Term	Explanation	Value
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{RC}$	LCI due to the recycling process related to the recycled content (including LCI of material losses during the recycling process)	LCI / unit of input material
$E_{RRE}$	LCI due to the recycling process related to the recycled material produced at the end of life (including LCI of material losses during the recycling process)	LCI / unit of input material
RC	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
RRE	End-of-life recycling rate (recycled or recovered material collected at the end-of-life divided by the available material after the use phase)	$0 \leq \dots \leq 1$
$C_{RC}$	Conversion efficiency of the recycling process related to the recycled content	Unit of useful output / unit of input material
$C_{RRE}$	Conversion efficiency of the recycling process related to the end-of-life recycling rate	Unit of useful output / unit of input material
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$Q_{RRE}/Q_v^*$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RC}/Q_v)^{-1}$
$A_{RRE}$	Market-price ratio between the recycled material and the displaced primary material in the subsequent life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RRE}/Q_v^*)^{-1}$

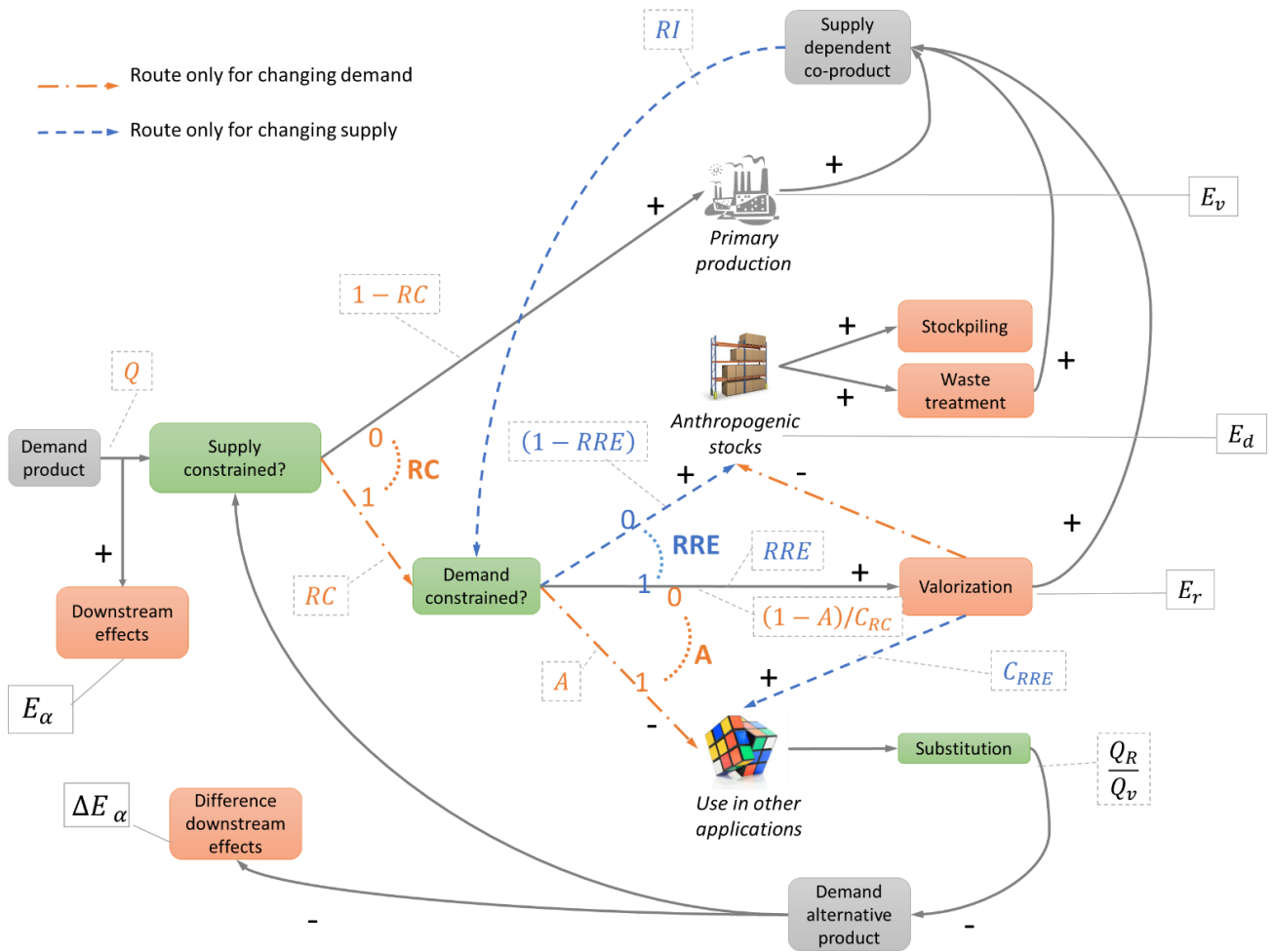


Figure 6-10 Causal Loop Diagram to identify the affected processes due to a changing supply or demand of a complex product, corresponding to Equation E5

#### 4.2.2.1. Effects of an increased demand for a material

In this and the following sections, we walk through the consequences that take place due to a changing demand or supply of a material, and how these consequences are represented by the terms of the equations. The effects that are caused by the changing demand for a material are shown in Figure 6-11 and Figure 6-12. The total quantity of the demanded material is represented by  $Q$ . The share of the material that is recycled is indicated by recycled content ( $RC$ ).

The increased demand for this material could lead to downstream effects in the foreground system. These effects are part of the cradle-to-gate or cradle-to-grave system boundaries of the LCA. The part of the material that is not recycled is produced by the marginal supplier of the primary resource. For the proportion of the recycled material for which there was no previous demand ( $1 - A$ ), the increased demand could lead to increased recycling ( $E_r$ ) and decreased waste treatment ( $E_d^*$ ). However, the material could also have been used in other product systems. In that case, increased demand for this material does not lead to increased recycling. Instead, in the alternative product system the recycled material might be replaced by a quantity of primary material. The alternative system does not anymore experience the downstream effects of using recycled material. The quality factor represents the quantity of primary material that is needed to replace the recycled material. This leads to increased impacts due to the primary production process of this material ( $E_v$ ). This is calculated for the fraction for which demand already existed ( $A$ ).

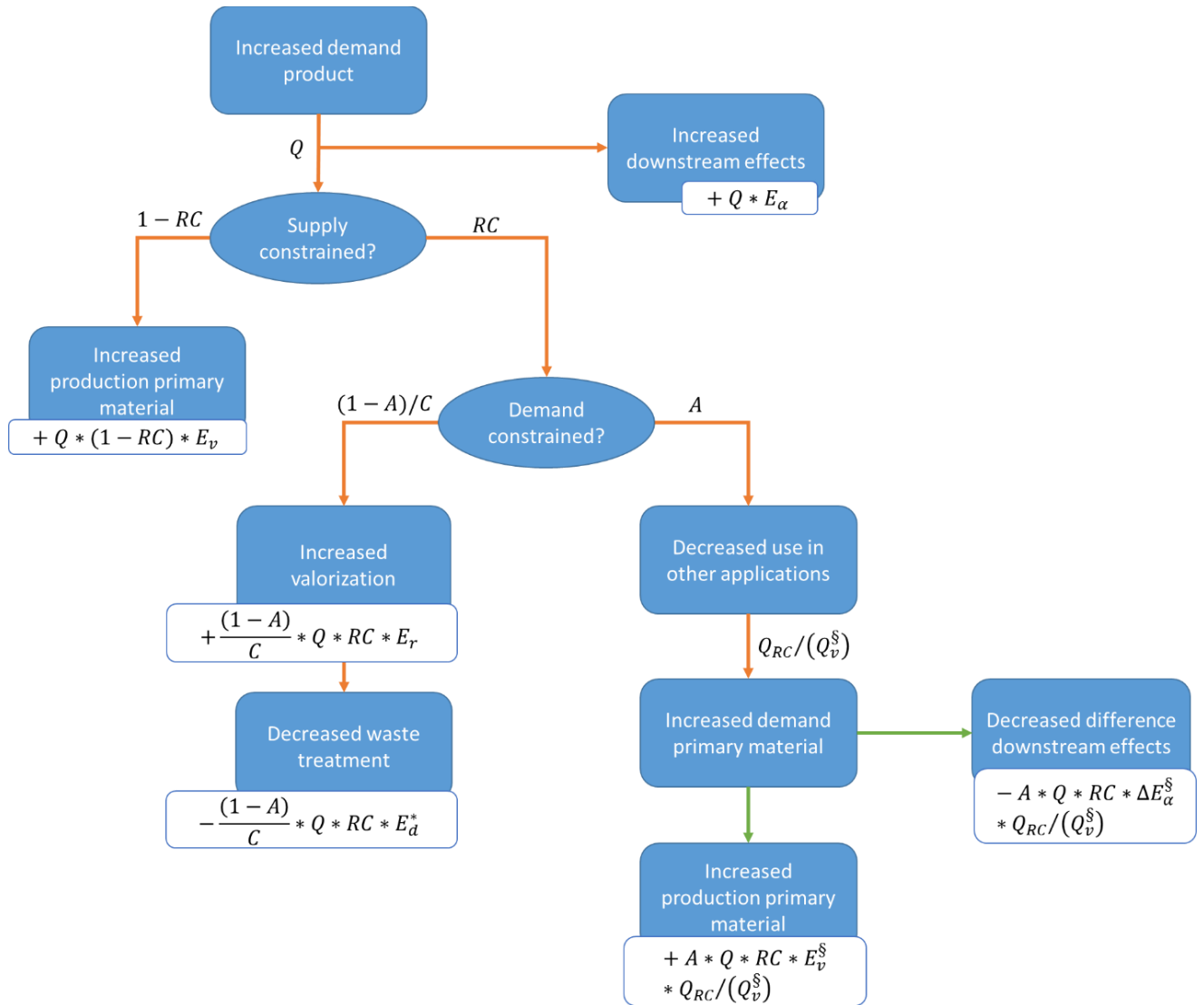


Figure 6-11 Indirect effects of an increased demand for recycled material.  $Q$ ,  $RC$ ,  $(1 - A)/C$ ,  $A$  and  $Q_{RC}/(Q_v)$  represent sizes of flows, which are multiplied with the inventory related to indirect effects ( $\Delta E_\alpha$ ), the recycling process ( $E_r$ ), waste treatment ( $E_d$ ) and primary production processes ( $E_v$ ). The superscripts \* and § indicate processes that take place in other product systems. Increased impacts are represented by a plus sign and avoided impacts by a minus sign. The different colors of the arrows represent the changing materials under study

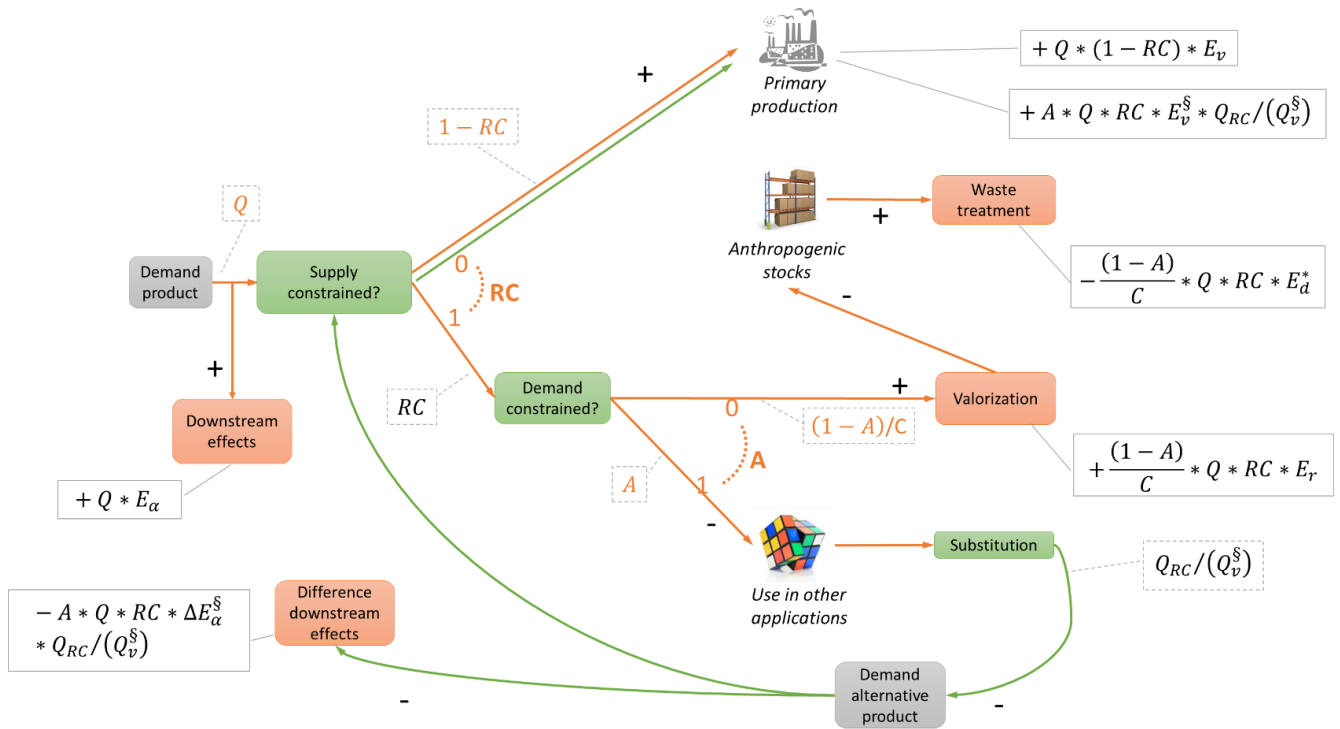


Figure 6-12 Causal Loop Diagram focusing on the indirect effects due to an additional demand for a material

#### 4.2.2.2. Effects of an increased supply of a material

The effects of an increased supply of a material are shown in Figure 6-13 and Figure 6-14. The supply is quantified by the production rate of the intermediate flow ( $RI$ ). The share of this intermediate flow that is recycled is represented by the (end-of-life) recycling rate ( $RRE$ ).

The share of the intermediate flow that is not recycled is treated as waste, by the marginal waste treatment process. The share that is recycled will undergo a “valorization” process. The valorized – or recycled – material can be used in other applications. However, now the question arises whether this recycled material will substitute primary material or whether it will avoid recycling in other product systems if the demand for this recycled material is limited. To solve this question systematically, first, it is assumed that other recycled material is displaced, which in its turn might displace primary material elsewhere.

First, it is calculated what quantity of other recycled material can be substituted by the recycled material under study, using the quality correction factor  $Q_{RRE} / (Q_{RRE}^s)$ . Then, it is determined whether the demand for this alternative recycled material is constrained: will the additional material available be absorbed by the market? This can be measured by the relative net economic benefits of using recycled material instead of primary material, i.e. the market-price ratio between the recycled and the primary material.

For the proportion for which the demand is constrained ( $1 - A$ ), the recycling activity will lead to decreased valorization and increased waste treatment in the alternative product system. This is calculated for the quantity of displaced recycled material. For the proportion for which demand is not constrained ( $A$ ), the supplied recycled material leads to increased use of the alternative recycled material in other applications where primary material can be displaced. The total net avoided production of primary material is calculated by the relative quality of the recycled material in the current product system compared to the quality of the primary material ( $Q_{RRE} / (Q_v^*)$ ).



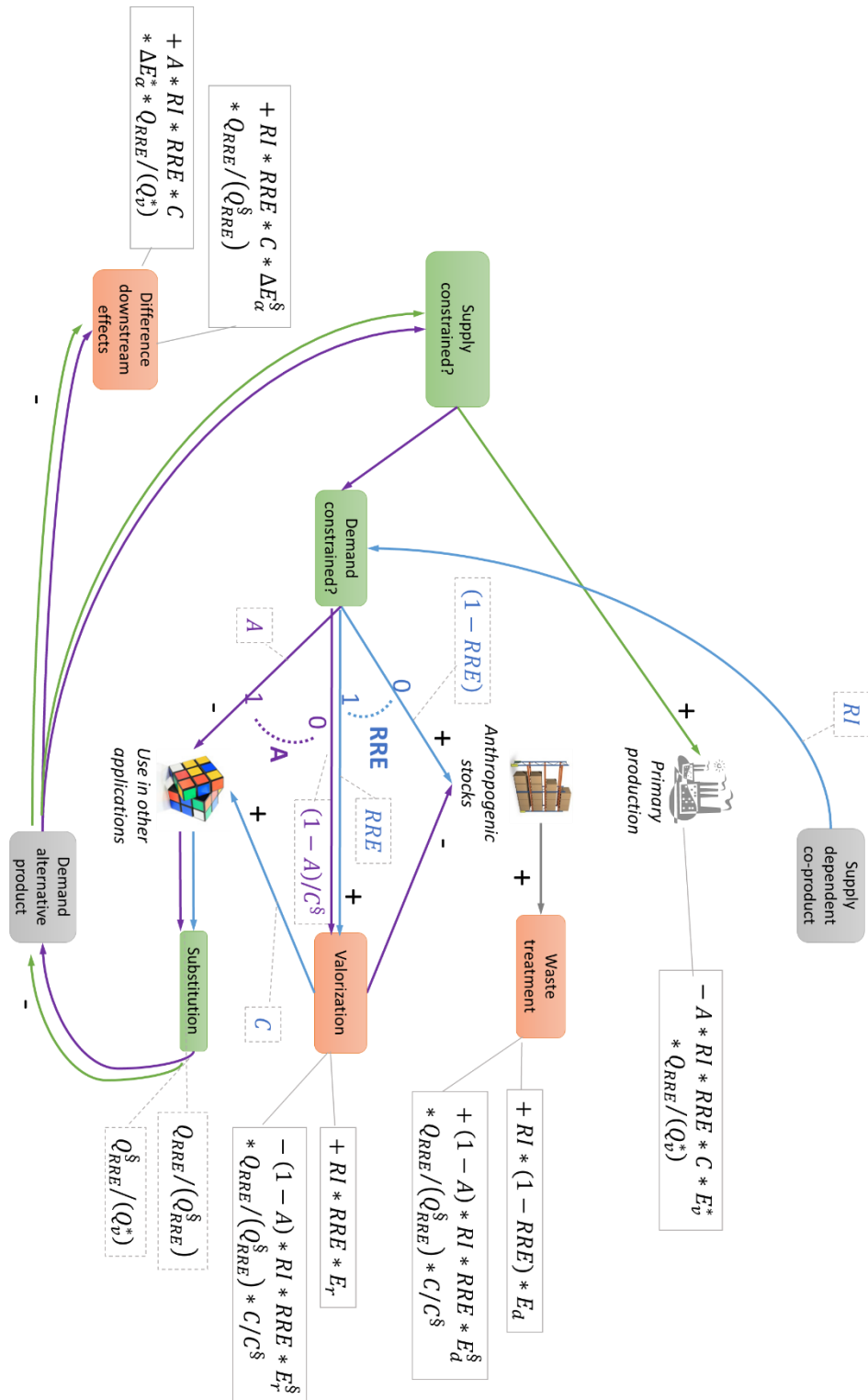


Figure 6-13 Causal Loop Diagram focusing on the indirect effects of the additional supply of a dependent co-product

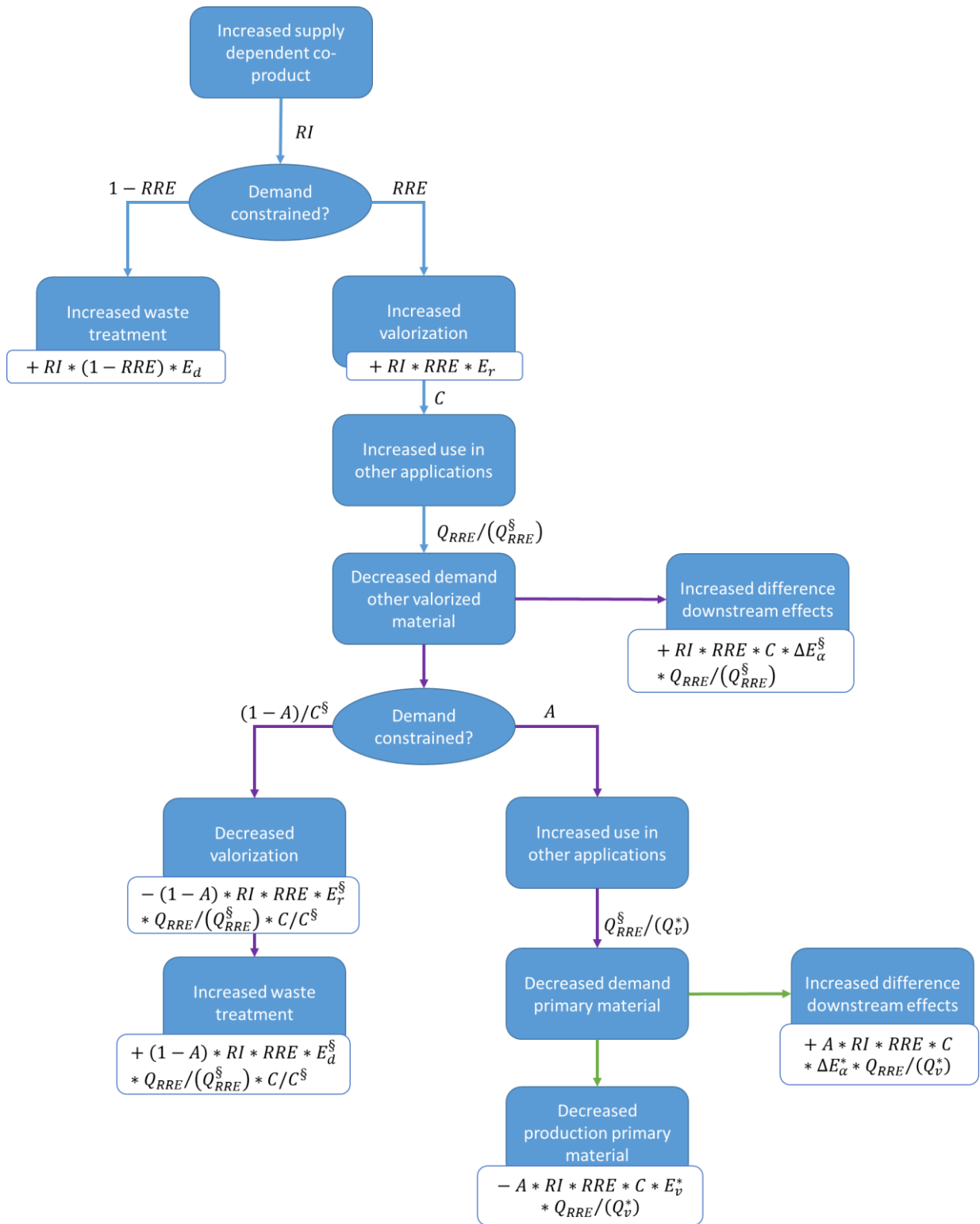


Figure 6-14 Indirect effects of an increased supply of recycled material.  $RI$ ,  $RRE$ ,  $(1 - A)/C$ ,  $A$ ,  $Q_{RRE}/(Q_{RRE}^S)$  and  $Q_{RRE}/(Q_v)$  represent sizes of flows, which are multiplied with the inventory related to indirect effects ( $\Delta E_\alpha$ ), the recycling process ( $E_r$ ), waste treatment ( $E_d$ ) and primary production processes ( $E_v$ ). The superscripts \* and § indicate processes that take place in other product systems. Increased impacts are represented by a plus sign and avoided impacts by a minus sign. The different colors of the arrows represent the changing materials under study

## 4.2.2.3. Buildup of a formula for complex products

In this section, the buildup of the inventory of a product in which recycled materials are consumed *and* produced is explained. The inventory combines all terms of Figure 6-11 and Figure 6-14, which results in the following equation (omitting Q and RI for clarity):

$$\begin{aligned}
 E6. \quad E_{tot} = & E_{\alpha} + (1 - RC) * E_v + (1 - RRE) * E_d + \frac{(1-A_{RC})}{C_{RC}} * RC * (E_{RC} - E_d^*) + A_{RC} * RC * \\
 & \frac{Q_{RC}}{Q_v^S} * (E_v^S - \Delta E_{\alpha RC}^S) + RRE * (E_{RRE} + C_{RRE} * \Delta E_{\alpha RRE}^S * Q_{RRE} / (Q_{RRE}^S)) - (1 - A_{RRE}) * \\
 & RRE * \frac{Q_{RRE}}{Q_{RRE}^S} * \frac{C_{RRE}}{C^S} * (E_{RRE}^S - E_d^S) - A_{RRE} * RRE * C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * (E_v^* - \Delta E_{\alpha}^*)
 \end{aligned}$$

This equation is built up by the following elements:

- Downstream effects due to the use of the material =  $E_{\alpha}$

Inventory related to the use of the material. The extent to which this is modeled is dependent on the scope of the study – only effects that take place in the foreground system are modeled. This could be related to the use of transport, manufacturing processes, inventory during the use phase or waste treatment.  $E_{\alpha}$  represents the net inventory of the mix of recycled and primary material.

- Consumption of primary material =  $(1 - RC) * E_v$

Inventory related to extraction and processing of primary (virgin) material.

- Waste disposal =  $(1 - RRE) * E_d$

Inventory related to the waste treatment of the fraction of the material that is not recycled at the end of life.

- Direct effects of the demand for recycled material =  $\frac{(1-A_{RC})}{C_{RC}} * RC * (E_{RC} - E_d^*)$

Inventory related to the recycling processes that take place due to the increased demand for recycled material, as well as avoided inventory due to the avoided waste treatment of this material. Avoided waste treatment is not necessarily landfilling. Avoided waste disposal could encompass incineration with energy recovery. This is represented by the marginal waste treatment process. The avoided benefits if this disposal process – e.g. avoided production of primary energy or another primary material – must be modeled within  $E_d^*$  as well. This term is only calculated for the fraction of the recycled material for which there is a limited demand (i.e.  $1 - A_{RC}$ ). For this fraction, the increased demand actually leads to increased recycling. The LCI for these processes is expressed per unit of waste material entering the waste treatment process or the valorization activity. The factor C converts this to the unit of recycled material.

- Indirect effects of the demand for recycled material =  $A_{RC} * RC * \frac{Q_{RC}}{Q_v^S} * (E_v^S - \Delta E_{\alpha RC}^S)$

Inventory related to the processes that indirectly take place due to the increased demand for recycled material, for the fraction that would otherwise have been used in other process systems (i.e.  $A_{RC}$ ). Diverting the recycled material from other process systems could lead to the increased demand for primary material in these other systems. However, this also results in decreased (or increased) downstream effects due to the use of recycled material instead of primary material, such as additional inventory related to transport of a heavier material.

- Direct effects of the supply of recycled material =  $RRE * (E_{RRE} + C_{RRE} * \Delta E_{\alpha RRE}^S * Q_{RRE} / (Q_{RRE}^S))$

Inventory related to the recycling process of the recycled material that is supplied at the end of life. If this material displaces recycled material from other product systems, additional inventory might be caused by the use of this recycled material instead of the alternative recycled material.

$$- \text{Indirect effects of the supply of recycled material} = -(1 - A_{RRE}) * RRE * \frac{Q_{RRE}}{Q_{RRE}^S} * \frac{C_{RRE}}{C^S} * (E_{RRE}^S - E_d^S) - A_{RRE} * RRE * C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * (E_v^* - \Delta E_\alpha^*)$$

Inventory related to processes that indirectly take place due to the increased supply of recycled material at the end of life. The fraction of the supplied recycled material for which there is a limited demand (i.e.  $1 - A_{RRE}$ ) could substitute recycled material from other product systems. This substituted recycled material will no longer undergo the recycling process, but is instead treated as waste. The fraction of the supplied recycled material for which there is enough demand (i.e.  $A_{RRE}$ ) can be used in other product systems where it could substitute a primary material. Again, some indirect downstream impacts (or benefits) related to the used recycled material can take place, which must be modeled as well.

#### 4.2.2.4. All exchanges take place via the market

Primary material and recycled material can be bought on the market. The material at the end of life can also enter a market for materials that need treatment. This treatment can encompass waste treatment or a recycling process. In the previous section, it is shown that the increased demand of recycled material can lead to a decreased use elsewhere, where primary Product<sup>S</sup> is now used. Also, the increased supply of recycled material could lead to a decreased supply of this material from other product systems, where now less recycling and increased waste treatment of Product<sup>S</sup> takes place. Product<sup>S</sup> is competing with the product under study in the same material market.

If all material exchanges in a product system take place via the market, only the marginal technologies for primary production, recycling, and waste treatment are affected by these interactions. The marginal primary production technology is the same in each product system when they are connected to the same market. This was illustrated by the example of the hydropower station for a hotel from Ekvall et al. (2005) in Chapter 2. Therefore, if products are bought and sold via the market, the following is valid:

$$E7. \quad E_v^S = E_v$$

$$E8. \quad Q_v^S = Q_v$$

A similar reflection is valid for the waste treatment and recycling processes. If a material is sent to an incineration facility, but this is already operating at full capacity, it might be landfilling that is affected. If incineration is reduced, waste might be bought from landfilling sites to keep the flow of material into the incineration facility constant. Similarly, waste can be redistributed over recycling facilities until only the marginal processes are affected. Hence:

$$E9. \quad E_d^S = E_d$$

$$E10. \quad E_{RRE}^S = E_{RRE}$$

However,  $E_d^*$  and  $E_v^*$  do not have to be the same as  $E_d$  and  $E_v$ , respectively. The valorization process can change the nature of the product, which happens in the case of open-loop recycling. The waste treatment that is avoided in the previous life cycle applies to the material before entering the recycling process, which is not necessarily similar to the recycled material that is produced by the recycling process. The primary material that competes with the recycled material can, therefore, also be different than the primary material in the previous life cycle.

If the recycled material that is supplied is similar to other recycled material in the market, and the difference in inventory for using recycled materials or primary materials is the same in different product systems, the following assumptions can be done:

$$E11. \quad Q_{RRE} / (Q_{RRE}^S) = 1$$

$$E12. \quad C_{RRE} = C^S$$

$$E13. \quad \Delta E_{\alpha RC}^S = \Delta E_{\alpha}$$

$$E14. \quad \Delta E_{\alpha RRE}^S = 0$$

With these simplifications it is possible to rewrite Equation E6 as follows:

$$E15. \quad E_{tot} = E_{\alpha} + (1 - RC) * E_v + (1 - RRE) * E_d + \frac{(1 - A_{RC})}{C_{RC}} * RC * (E_{RC} - E_d^*) + A_{RC} * RC * \left( E_v * \frac{Q_{RC}}{Q_v} - \Delta E_{\alpha} \right) + RRE * E_{RRE} - (1 - A_{RRE}) * RRE * (E_{RRE} - E_d) - A_{RRE} * RRE * C_{RRE} * \frac{Q_{RRE}}{Q_v} * (E_v^* - \Delta E_{\alpha}^*)$$

Rearranging the terms leads us back to Equation E5. The term  $+(1 - RRE) * E_d + (1 - A_{RRE}) * RRE * E_d$  could be further rearranged as  $(1 - RRE * A_{RRE}) * E_d$ , which shows that for each material for which  $A_{RRE} = 0$  waste treatment must be modeled. Therefore, it is not necessary to distinguish for this term between a waste and a co-product, and the arc referring to  $RRE$  in Figure 6-10 can be replaced by  $A_{RRE}$  as in the CLD in Figure 6-5 and Figure 6-9. All intermediate flows that are produced could be considered a co-product. Waste treatment can only be avoided if a valorization activity produces a material for which the demand is not fully constrained.

#### 4.2.3. From a recycling-oriented system to a production-oriented system

For some materials, it could be counter-intuitive to speak about “recycled content” or “recycling rate” while referring to their use or production, even though the materials are not a determining co-product. This could be the case for products that are only produced as dependent co-product but are generally not considered as a recycled material. An example could be the co-produced cerium from primary mining: although this product is not a determining co-product (as will be indicated in Chapter 7C), it is strange to speak of “recycled content” while referring to the use of this material. Similar as in Chapter 5, the parameters could be rewritten to make the use and production of recycled material more applicable to co-products in general. The Consumption Rate (CR) of a material can be calculated for a primary material:

$$E16. \quad CR_i = Q_i * (1 - RC_i)$$

And for a recycled material:

$$E17. \quad CR_i = Q_i * RC_i$$

We can calculate the Production Rate (PR) of a material as follows:

$$E18. \quad PR_i = RI_i * RRE_i * C_i$$

Furthermore, the inventory of the valorization processes had been expressed per unit of ingoing waste. Alternatively, the inventory can be expressed per unit of outgoing co-product, referring to the determining co-product of the valorization process:

$$E19. \quad E_{PRi} = E_{ri} / C_i$$

Whether the changing demand for a material will affect a primary production route or not is not determined by the fact whether it concerns a recycled material. Instead, we introduce a factor for the level of supply constraints:  $S$ . If supply is fully elastic, hence there are no supply constraints,  $S = 1$ . If supply is fully inelastic:  $S = 0$ .  $S$  can have any value between 0 and 1 if the elasticity of supply is somewhere between fully inelastic and fully elastic. As stated in Section 4.1, it can generally be assumed that the supply of a “determining co-product” is fully elastic, while the supply of a “dependent co-product”, such as a recycled material, is fully inelastic.

This gives us the following equation:

$$E20. \quad E_{tot} = \sum_{i=1}^n CR_i * E_{\alpha i} + \sum_{i=1}^n CR_i * S_i * E_{vi} + \sum_{i=1}^n CR_i * (1 - S_i) * \left( (1 - A_{RCi}) * \left( E_{CRi} - \frac{E_{di}^*}{C_i} \right) + A_{RCi} * \frac{Q_{RCi}}{Q_{vi}} * (E_{vi} - \Delta E_{\alpha i}) \right) + \sum_{i=1}^n PR_i * (1 - A_{RREi}) * E_{di} + \sum_{i=1}^n PR_i * A_{RREi} * \left( E_{PRi} + \frac{Q_{RREi}}{Q_{vi}^*} * (\Delta E_{\alpha i}^* - E_{vi}^*) \right)$$

This equation refers to the effects as shown in the CLD of Figure 6-15. It should be noted that the avoided demand for an alternative product could refer to a product of which supply is not fully elastic ( $S \neq 1$ ). However, in the equation it is assumed that the second iteration of the CLD refers to a product with fully elastic supply. For a more detailed analysis, the CLD can be followed instead.

Table 6-4 Legend of terms for Equation E20. In a product-oriented approach, “recycled” refers to a material with constrained supply, and “primary” to a material with unconstrained supply

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI / unit of analysis
$i$	Refers to an intermediate flow, recycled material or co-product that is used or produced in the life cycle of the product under study	
CR	Consumption rate of an intermediate flow per unit of the product under study	Rate $\geq 0$
PR	Production rate of a co-product per unit of the product under study	Rate $\geq 0$
$E_{\alpha}$	LCI due to the downstream impacts related to the use of the material in the functional unit	$E_{\alpha v} + \Delta E_{\alpha}$
$E_{\alpha v}$	LCI due to the downstream impacts if only primary material were used	LCI / unit of analysis
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the life cycle under study	LCI / unit of displaced primary material
$\Delta E_{\alpha}^*$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the subsequent life cycle	LCI / unit of displaced primary material

Term	Explanation	Value
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{CR}$	LCI due to the valorization process related to the consumed material (including LCI of material losses during the valorization process), per unit of the determining co-product of the valorization process	LCI / unit of co-product
$E_{PR}$	LCI due to the valorization process related to the produced material (including LCI of material losses during the recycling process), per unit of the determining co-product of the valorization process	LCI / unit of co-product
$S$	Rate of supply constraints. If supply is fully elastic, $S = 1$ . If supply is fully inelastic, $S = 0$	$0 \leq \dots \leq 1$
$C$	Conversion efficiency of the valorization process related to the consumed product	Unit of useful output / unit of input material
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$Q_{RRE}/Q_v^*$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RC}/Q_v)^{-1}$
$A_{RRE}$	Market-price ratio between the recycled material and the displaced primary material in the subsequent life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RRE}/Q_v^*)^{-1}$

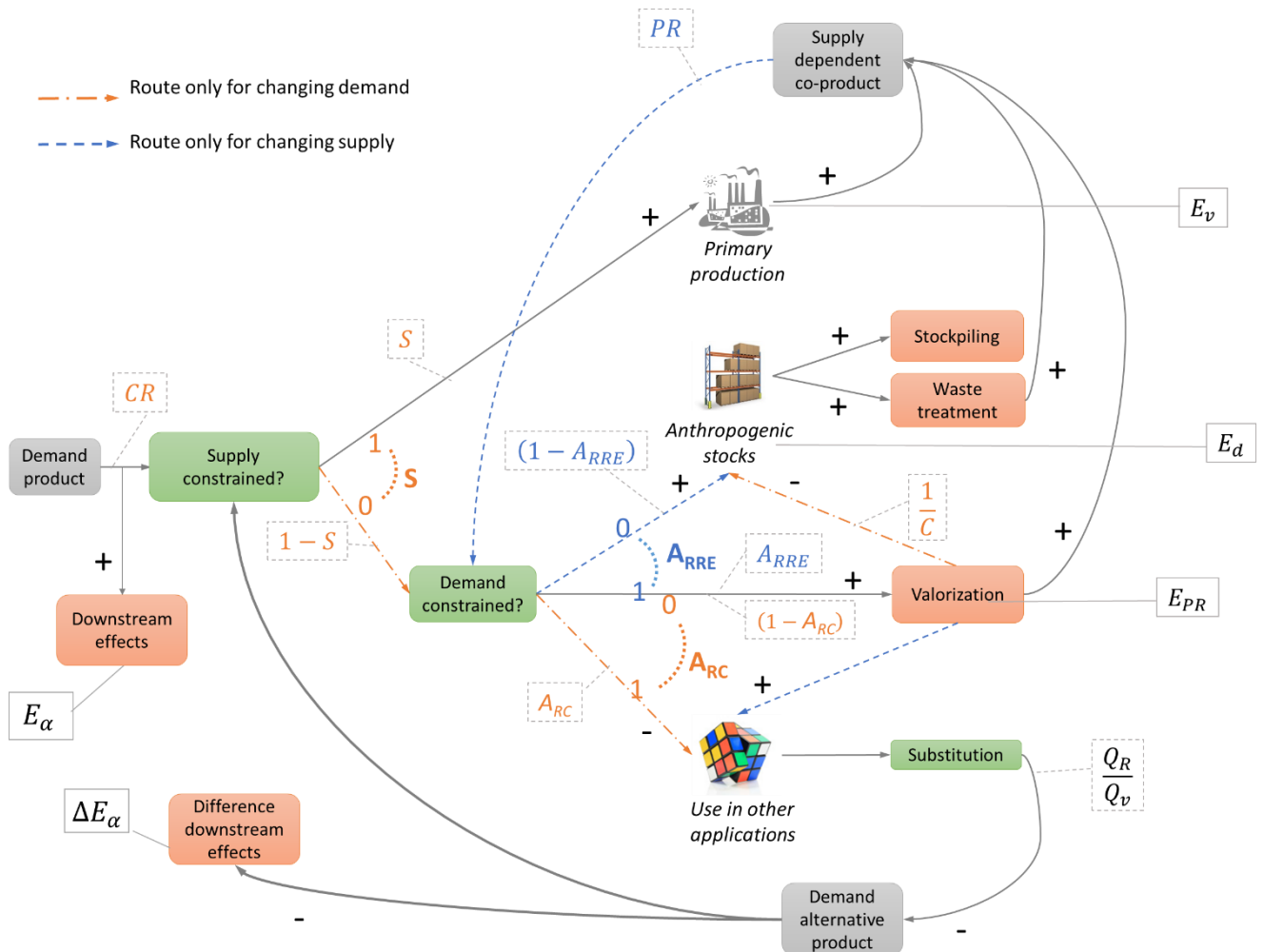


Figure 6-15 Application of the production-oriented perspective to the causal loop diagram of affected processes due to a changing supply or demand for a product. This CLD corresponds to Equation E20



#### 4.2.4. Simplified formula for missing inventory data

It might be difficult to identify all the (indirect) effects that take place in another product system where the material could be or could have been used. We imagine that the inventory of the recycling process is built up as follows:

$$E21. \quad E_{RC_{tot}} = E_{RC1} + E_{RC2} + \Delta E_{\alpha}$$

And

$$E22. \quad E_{RRE_{tot}} = E_{RRE1} + E_{RRE2} + \Delta E_{\alpha}^*$$

Where the recycled material is traded between Recycling Processes 1 and 2. The company that executes Recycling Process 1 might not have knowledge about Recycling Process 2 and the additional indirect inventory.  $\Delta E_{\alpha}$  related to the recycled content is already modeled in the foreground system where the recycled material is used, as it is part of  $E_{\alpha}$ . We could make the simplifying assumptions that there are no demand constraints and the market price is linearly related to the (environmental impact of the) recycling efforts and the indirect downstream effects. This means that the price that can be identified between Recycling Processes 1 and 2 might reflect the additional inventory that is related to the recycled material, relative to the valorization process that already took place.

This assumption is only valid when it is reasonable to state the following (a similar analysis can be applied to the valorization process of the recycled content):

$$E23. \quad \frac{E_{RRE2} + \Delta E_{\alpha}^*}{E_{RRE1}} = \frac{1 - A_{RRE}}{A_{RRE}}$$

And

$$E24. \quad E_{RRE2} + \Delta E_{\alpha}^* = (1 - A_{RRE}) * C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * E_v^*$$

Note that this does not represent actual impacts, as the impacts related to the second part of the recycling process and the indirect effects can be of completely different nature than the impacts of the first part of the recycling process and the avoided primary process. With this assumption, the simplified formula would be as follows:

$$E25. \quad E_{tot} = \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{E_{RC2_i}}{C_{RC_i}} + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * E_{v_i} \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \sum_{i=1}^n RI_i * RRE_i * \left( E_{RRE1_i} - A_{RRE_i} * C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * E_{v_i}^* \right)$$

In this equation,  $A$  is not determined after the valorization step but at the moment where the transaction takes place. If this is between the two sub-processes 1 and 2 of the valorization process, only the processes within the company boundaries are modeled. There are no indirect effects related to increased or avoided waste treatment elsewhere, due to the assumption of no demand constraints. The equation can be applied when the market-price ratio is lower or higher than 1. However, it should be noted that not all indirect effects are relevant for the user of the recycled material. This means that they might not be taken into account in the market price. Therefore, instead of using market prices as a proxy, in all cases it is preferable to model the actual (downstream) effects as they take place.

## 5. Discussion

In this section, the limitations of the causal loop diagram are discussed, the methodology is compared to similar approaches for consequential LCA, and it is discussed whether the presented approach is compliant with ISO 14044.

### 5.1. Limitations of the causal loop diagram

The Causal Loop Diagram (CLD) that is presented in this chapter enables to identify the consequences of a changing demand for a product. However, the mechanisms that were taken into consideration are limited. The type of consequences that is taken into consideration is mainly based on the work of (Ekvall 2000; Weidema et al 2009). Ekvall et al. (2005) argue that consequential LCA is subject to subjective choices, such as the level of detail that is modeled in the LCA. One important limitation of the application of consequential LCA in this chapter (and in the case study of Chapter 7C) is the *ceteris paribus* assumption: it is assumed that the demand for products that are not part of the functional unit stays the same. A decreased availability of a material in the market does not necessarily lead to the substitution of another material. For example, the rare earth supply crisis of 2010 has led to a more efficient use of REEs in products (ERECON 2014). However, efficiency improvements might require technology developments in the long term. Technology developments can be taken into consideration in an LCA study that assesses consequences on the *very long term*, while such developments are often considered outside the scope an LCA focusing on the long term (Frischknecht 1998).

In this chapter, the market-price ratio between a recycled material and a substituted primary material is used to identify demand constraints as well as the level of substitutability. When a material has a low market-price ratio, it was considered that substitution might take place in another market segment. It could be interesting to discuss whether products in the lowest market segments actually provide a functionality or whether the market segment exists due to the availability of cheap (scrap) materials. There has been an increase in the availability of products made from recycled materials, such as plastic bags. We should consider whether a decreased availability for plastic to produce these bags actually leads to an increased production of primary plastic for plastic bags, or whether fewer bags will be produced altogether. In the latter case, the application merely serves as postponed waste treatment (Geyer et al 2015). The function of the recycled product might be even considered irrelevant. The availability of cheap products could serve a market in two ways: the lower quality of a product requires that the product is more often replaced compared to a product in a higher market segment. This could lead to additional impacts related to production or valorization and waste treatment. However, the lower market segment is not necessarily more impactful than the higher market segments. This depends on the materials that are used in the different products. A lower price of the product could also lead to an increased consumption due to the rebound effect. People might purchase more of a product than they actually need, i.e. the efficiency of the product to provide a function is decreased. Effects on efficiency could be added in the causal loop diagram. Rebound effects are gaining interest in the LCA domain (Girod et al 2011; Vivanco 2016). A difference in price between a recycled and a primary material could lead to a larger consumption of the recycled product than required for the same functionality. The limited environmental benefits that are attributed to the production of a material with a low price – and a low market-price ratio – might be able to correct for this effect. However, a deeper analysis into potential rebound effects and factors to take this into account is suggested for further research.

Although the number of mechanisms that is included in the CLD is limited, Ekvall, Tillman, & Molander (2005) argue that is generally impossible to model all the consequences of an action in LCA. As long as it is not known what the potential impact is of the consequences that are excluded from the analysis, it is impossible to know whether the results of the LCA represent reality (Ekvall et al 2005). This is the risk of any investment decision. Decisions are based on the information that can be acquired, and time will learn whether important interactions or consequences have been overlooked.

## 5.2. Comparison with other methods

The consequential LCA methodology applied in this thesis is not the only possible application of consequential LCA. Especially the use of price elasticity is popular under LCA analysts that conduct c-LCA. We shortly discuss the merits and the drawbacks of the current approach. Furthermore, a comparison is done with a recently developed allocation formula of the European Commission, which shows similarities with the formulas of the consequential methodology presented in this chapter.

### 5.2.1. Models based on price elasticities

The limitations of price elasticities were extensively discussed in Chapter 3. These limitations have motivated us to propose the market-price ratio between a recycled material and the substituted primary material as an indicator for demand constraints. Kätelhön et al. (2016) discuss the benefits of an approach that considers only production costs over partial equilibrium and general equilibrium models. Process-based information can be easier to acquire and represents more detailed information than econometric models (Kätelhön et al 2016). While price elasticities assume rational behavior, market prices can act as indicators for different market behavior. However, price elasticities consider market-wide behavior which might not be represented by market prices. Therefore, price elasticities could provide complementary information to an analysis based on our approach. It was already stated in Chapter 3 that the marginal user could be identified by a high price elasticity of demand. Zink et al. (2015) discuss the possibility that recycled and primary materials are complements of each other instead of substitutes. This has not been considered in the approach of this thesis. We consider the use of cross-price elasticities as a useful addition to our approach to identify the degree of substitutability or complementarity of materials, which also helps to calculate downstream consequences related to the substitution.

Price elasticities are difficult to calculate and are not widely available. Therefore, market prices can provide a first selection of potential substitutes, after which price elasticities can be collected for these substitutes to quantify the substitutability and, potentially, rebound effects. Market prices can further aid in identifying downstream consequences. This information could help to calculate more realistic consequences, and it could support policy measures, which is discussed in Chapter 8. It is true that prices can fluctuate, which is often brought up as a drawback in LCA (Werner and Richter 2000). However, the market price of recycled material is often connected to the price of primary material (Frees 2008; Plastics Recyclers Europe 2012). Therefore, market-price ratios are considered to be more stable than absolute market prices. Furthermore, a relation between the market price, the recycling effort and the demand for the material had already been suggested in previous studies (Plastic ZERO 2013; Koffler and Florin 2013).

Several possible interpretations for the market-price ratio have been identified. Future case studies can indicate whether other interpretations could be possible as well, and in what situations the market-price ratio is not a good indicator for demand constraints. The use of economic factors in the calculation of environmental consequences can also provide benefits. If the market price does not represent the market situation of the recycled material, subsidies could be applied to stimulate the production or consumption of this material. This is further discussed in Chapter 8.

### 5.2.2. Circular Footprint Formula

The European Commission is working on a new formula which will replace the End-of-Life formula of the PEF Guide (European Commission 2013): the Circular Footprint Formula (CFF) (Zampori et al 2016). The latest version of this formula shows similarities with the formulas provided in this chapter. Below, the basic formula of Section 4.2.1 (Equation E4) is copied. Elements that are included in the CFF are represented bold. Elements that are not part of the CFF are gray. The CFF differentiates between recycling at the end of life ( $RRE_{mat}$ ) and energy recovery ( $RRE_{energy}$ ), so the term RRE is differentiated in

Equation E26 as well. Note that the terms in Equation E26 are not entirely the same as the terms in the CFF. In the comparison, it is aimed to represent only major differences.

$$\begin{aligned}
 \text{E26. } E_{tot} = & E_{\alpha} + (1 - RC) * E_v + RC * \left( \frac{(1-A_{RC})}{C_{RC}} * (E_{RC} - E_d^*) + A_{RC} * \frac{Q_{RC}}{Q_v} * (E_v - \right. \\
 & \left. \Delta E_{\alpha}) \right) + (1 - RRE_{mat} - RRE_{energy}) * E_d + RRE_{mat} * \left( (1 - A_{RRE}) * E_d + A_{RRE} * \right. \\
 & \left. (E_{RRE} + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * (\Delta E_{\alpha}^* - E_v^*)) \right) + RRE_{energy} * \left( (1 - A_{RRE}) * E_d + A_{RRE} * \right. \\
 & \left. (E_{RRE} + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * (\Delta E_{\alpha}^* - E_v^*)) \right)
 \end{aligned}$$

Although several terms of the Equation E4 from Section 4.2.1 are similar as the CFF, there are important differences:

- The CFF does not model increased or avoided waste treatment when a recycled material is supplied or consumed, respectively, for which there is a low demand.
- The CFF does not consider indirect effects that take place in the life cycle in which recycled material is used, compared to the use of primary material.
- $RRE_{mat}$  refers to the amount of recycled material that is produced by the recycling plant, corresponding to  $RRE * C_{RRE}$  in terms of this thesis. This means that waste disposal  $E_d$  is calculated for inefficiencies of the recycling process as well. However, the impacts of the recycling process also refers to “specific emissions [...] arising from the recycling process at EoL. There is a risk that waste disposal of losses during the recycling process is double counted.  $RRE_{energy}$  refers to the amount of waste that is sent to a recovery facility. A conversion factor similar to  $C_{RRE}$  is multiplied with the recovery rate to calculate the amount of recovered energy.
- Recovered energy is only included for the production at the end of life. This is not necessarily a problem, as the default value for  $A_{RRE}$  for recovered energy is 1. However, if this value would be different, the use of recovered energy should be modeled as well, similar to the recycled content of materials. However, the equation of the CFF does not include a term for this.
- The A-factor of the CFF represents the market situation of the recycled material. If there is a low offer of recycled material and a high demand,  $A = 0.8^5$ . If there is a high offer of the recycled material and a low demand,  $A = 0.2$ . Therefore, full substitution is not always modeled. However, the consequences of a partial substitution are not included in the formula. Also, in the CFF, it is considered that material is substituted which contains recycled material as well. It is unclear what the consequences are of this avoided use of recycled material. In this thesis, this is modeled as an additional waste treatment. It is possible that the additional supply leads to an additional demand without substitution taking place, e.g. considering the rebound effect. However, in that case, A should perhaps not be multiplied with the recycling process if it is expected that this process still takes place. It is true that the simplified formula of this chapter (Equation E25) also does not model increased or avoided waste treatment. However, this formula can only be applied if the A-factor represents additional downstream effects, and

<sup>5</sup> In fact, the Circular Footprint Formula applies an inverse value for A.  $A = 0.8$  in case of a low demand and 0.2 in case of high demand. The values A and (1-A) are also inversed in the CFF. For clarity, we represented the formula in a similar way as the other formulas in this chapter.

there are no demand constraints. The definition of the A-factor in the CFF represents the existence of demand constraints, which makes the simplified formula unsuitable for comparison.

The European Commission also provides a list of A-values for different materials, such as metals, paper, plastics, glass and wood (Zampori et al 2016). These values could serve in the application of our approach as well. However, it should be considered that different material grades, locations or contexts could provide different demand constraints. Therefore, we consider it preferable to use the market-price ratio to calculate A. The difference between the methodology provided in this thesis and the formula of the European Commission suggests that the CFF does not provide a full consequential approach. However, the CFF is a large improvement compared to the End-of-Life formula of the PEF Guide (European Commission 2013) with regard to the consistency of the approach.

### 5.3. Compliance of the consequential methodology with ISO 14044

Whether ISO 14044 represents an attributional or a consequential LCA is often discussed in the LCA community. This has also been analyzed in the critical review of the standard in Chapter 4. According to the standard, allocation can be avoided by applying subdivision or system expansion. If allocation cannot be avoided, allocation should be based on physical relationships or other relationships.

#### 5.3.1. Subdivision

Subdivision is described in ISO 14044 by *“dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes”* (ISO 2006a).

Subdivision is applied on different levels in the presented consequential approach. Subdivision can be applied between different life cycle stages, such as production, valorization and waste treatment. Input and output data for these life cycle stages can be separately collected and modeled. Subdivision is also applied within a multifunctional process. For example, when a valorization process produces multiple co-products, the process is subdivided to only represent the production of one determining co-product at a time. However, subdivision does not always avoid having to model other sub-processes, e.g. when the consequences of the production of an intermediate flow are the subject of the study.

#### 5.3.2. System expansion

In Chapter 3, it was stated that system expansion is often used as a synonym for “substitution”, which was assimilated to the modeling of the consequences of the production of a co-product. In that case, following the Causal Loop Diagram would be a legitimate interpretation of “system expansion”. However, in this thesis, another interpretation of system expansion was applied: the inclusion of multiple functions in the functional unit. It appeared that system expansion can prevent to model the consequences of the production or treatment of intermediate flows, and thereby simplify the analysis. However, it was also discussed that these consequences provide useful information. Knowledge of these consequences is often the purpose of conducting the LCA. Therefore, it was concluded that system expansion does not always provide the information that is sought for in the LCA goal definition.

#### 5.3.3. Physical relationships

If subdivision and system expansion cannot be applied, allocation can be applied based on physical relationships: *“Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.”*

It was already discussed in Chapter 5 that allocation based on physical relationships is only relevant in the case of combined production, where the output of one of the functions of a multifunctional process

can be avoided if this is not part of the functional unit. One could argue that the physical output of a recycled product or co-product can avoid the production of these products by a primary route. However, this causal relationship is economic, and not physical (Ekvall and Finnveden 2001; Geyer et al 2015).

#### 5.3.4. Other relationships

*“Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products”*

The Causal Loop Diagram models the consequences of the supply or demand of a product based on causal economic relationships. The economic value of products is used to identify whether demand constraints exist. Therefore, it can be concluded that the approach is compliant with the requirements of ISO 14044.

#### 5.3.5. Other requirements of ISO 14044 and specific requirements for recycling

ISO 14044 discusses further requirements for the allocation procedure. These have been discussed in the context of an attributional LCA in Chapter 5 (Sections 4.4.5 and 4.4.6). It is our impression that these requirements refer to the interpretation of ISO from an attributional perspective. Several of these requirements refer to the location of the system boundaries with respect to the recycling process, while the modeling of effects in consequential LCA goes beyond the system boundaries of the foreground process. In that sense, system expansion is applied to include the whole world within the system boundaries, which avoids the need for allocation in the first place. Therefore, the additional requirements for allocation are not further discussed in the context of a consequential LCA.

## 6. Conclusions

This chapter presents a methodology to identify the consequences of a change, such as an increased demand for a product. Many parts of this methodology have been based on currently available guidelines; especially from Ekvall (2000) and Weidema et al. (2009). In consequential LCA, the consequences of the supply of or demand for a material are often based on price elasticities. The use of price elasticities has limitations due to the limited availability of data that represent the relevant materials and time horizons, and the limited information that price elasticities provide. Besides, stockpiling had been identified as a missing element in current consequential modeling.

Several shortcomings of the current application of consequential LCA have been addressed in this chapter. It has been considered before that the demand for a dependent co-product – i.e. a recycled product or a co-product that does not determine the production volume of an activity – can be constrained, as discussed in Chapter 3. In that case, it is generally assumed that the product is treated as waste. In this chapter, we demonstrated that dependent co-products for which demand is constrained are not always disposed of as waste. Primary products – such as ammonium sulfate and several rare earth elements – that are produced in surplus are rather stockpiled. Stockpiles can be – together with waste flows – considered as *anthropogenic stocks*. Anthropogenic stocks are identified as the marginal supplier of dependent co-products for which demand is constrained.

It is also commonly assumed in consequential LCA that materials are traded on the market. However, also this is not always the case. Some dependent co-products are directly traded between two actors within a value chain. Also in this situation, both constraints of supply and demand can be relevant. Analogous to dependent co-products that are traded on the market, it must be identified which constraints are dominant.

The consistency of the existing methodology for consequential LCA is further enhanced by considering that each process has only one determining co-product. It has been argued elsewhere (e.g. by Weidema et al. (2013)) that some materials do not have an alternative production route and require a different allocation procedure. However, in practice, each material could be substituted – if not by another material, by another product or technology, or even by a completely different system that provides the same function.

It was concluded in Chapter 3 that price elasticities are not sufficient to identify the relative constraints of supply and demand in each situation and in all product groups. In this chapter, the market-price ratio  $A$  between the recycled and the primary product is proposed as an alternative indicator to identify demand constraints. This factor can operate as a switch between the three substitution methods that were identified in Chapter 3:

- The waste mining method is applied when  $A = 0$
- The 50/50 method is applied when  $A = 0.5$
- The end-of-life recycling method is applied when  $A = 1$

This indicator is found to represent the existing preferences of the metals and plastics sectors. Besides, the method is also applicable to other materials. Factor  $A$  is integrated into the market-driven substitution method. This equation is written in the same style as the formulas of Chapter 3.

A Causal Loop Diagram is presented as a tool to identify the affected processes due to a changing demand for a product, or a changing production by a process. It is demonstrated how the market-driven substitution method relates to the Causal Loop Diagram. While the market-driven substitution formula has a bounded scope – as it assumes that the supply of the substituted primary material is unconstrained – the Causal Loop Diagram allows identifying the consequences of a change in more detail.

The market-driven substitution method has also been presented in a form that enables to assess complex products and a form that applies a production-oriented terminology. A simplified equation is introduced as well, which can be used to approximate environmental impacts when inventory data is lacking.

The methodology for consequential LCA as applied in this thesis is found to be compliant with the ISO standards and shows several benefits in respect to other consequential methodologies, such as partial equilibrium modeling. However, it is acknowledged that price elasticities would improve the methodology of this thesis on several aspects: the marginal user could be identified by a high price elasticity of demand and the degree of substitutability or complementarity of two co-products could be identified by cross-price elasticities. Market-price ratios are more easily available than price elasticities and could narrow down the alternative products for which elasticities should be collected. Furthermore, market-price ratios can help identifying the existence of downstream consequences that take place after substitution, which must be modeled in the LCI as well.

A demonstration of the application of this method is given in the consequential case study of Chapter 7 and in the case studies of Annex A and Annex B. In this thesis, it is the purpose to identify an LCA method that provides relevant answers for industrial stakeholders. Therefore, the choice between attributional LCA and consequential LCA and relevance of this consequential approach in an industrial context are further discussed in Chapter 8.



## Chapter 7: Application of the systematic framework for allocation to a case study on the recycling of rare earth elements from end-of-life fluorescent lamps

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In Chapter 3, a systematic framework was presented that demonstrates how different elements of the goal and scope definition influence the allocation procedure for recycling situations in the LCA. These items are the perspective of the LCA – i.e. whether an attributional or consequential approach is applied –, the reasons to carry out the study – i.e. a process-oriented or a product-oriented LCA – and the intended application. Furthermore, the intended audience influences several of these aspects, as well as the need to solve a multifunctional situation. The intended audience can, for example, be rather interested in the accountability for impacts or in impacts that are caused by a consumption of a product. If the intended audience is a company that operates a process, a process-oriented LCA might be the most suitable procedure and allocation might not be necessary. However, if the intended audience is a downstream user of a product, a product-oriented LCA should be applied and an allocation procedure is required to identify the impacts of the product.

The framework of Chapter 3 shows that partitioning can be applied in an attributional product-oriented LCA, and substitution in a consequential LCA. However, in Chapter 3, no specific guidance was provided on *how* to apply partitioning or substitution in different multifunctionality situations. This guidance has been developed in Chapters 5 and 6. In Chapter 5, the partitioning method “allocation at the point of substitution” (APOS) was identified as the most suitable method to apply partitioning in an attributional LCA. In Chapter 6, the market-driven substitution method was introduced that merges the three substitution methods of Chapter 3 – the end-of-life recycling method, the waste mining method, and the 50/50 method – into one single substitution method. The market-price ratio  $A$  between the recycled material and the substituted primary material operates as a switch between the three substitution methods of Chapter 3.

Based on the findings of the previous chapters, the systematic framework of Chapter 3 is updated in this chapter with the APOS method and the market-driven substitution method (Figure 7-1). Next, in the current chapter, the framework is applied to the case study of recycled rare earth elements of fluorescent lamps.

First, the goal and scope definition of the case study is presented. Each element of the framework is described in relation to the recycling of YOX. Based on the goal and scope definition, an attributional and a consequential approach are applied. Therefore, Chapter 7 is structured as follows:

- Chapter 7A: Goal and scope definition
- Chapter 7B: Attributional LCA
- Chapter 7C: Consequential LCA

Some elements of the goal and scope definition are valid for both an attributional and a consequential LCA. However, some elements are fundamentally different – such as the allocation procedure for a product-oriented LCA. Rather than presenting two separate goal and scope definitions for an attributional and a consequential LCA, Chapter 7A presents the goal and scope definition for both LCA approaches, while differentiating between the approaches when necessary. Therefore, the goal and scope of Chapter 7A serve both attributional and consequential case studies of Chapter 7B and Chapter 7C, respectively.



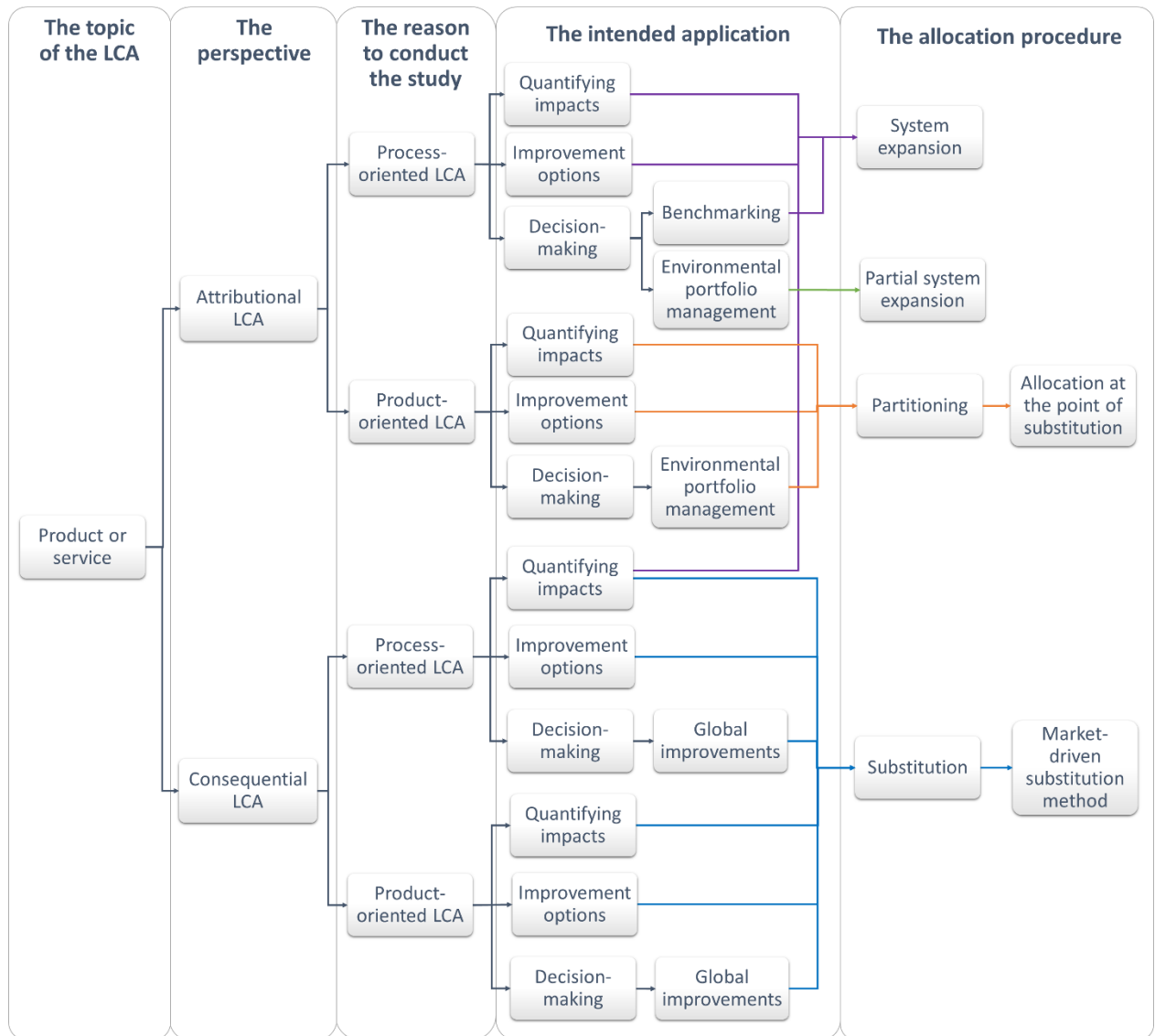


Figure 7-1 Updated systematic framework for consistent allocation in LCA based on the findings of Chapters 5 and 6

## Chapter 7A: Application of the systematic framework

### 1. Introduction

This section discusses the elements of the goal and scope definition that influence the allocation procedure as shown in Figure 7-1. Furthermore, other items of the goal and scope are discussed as well. Some elements influence indirectly the allocation procedure – such as the intended audience – while others are influenced themselves by the allocation procedure – e.g. data sources.

### 2. Goal and scope definition for attributional and consequential LCA

#### 2.1. The topic of the LCA

Fluorescent lamps function by interactions between phosphors – which contain REEs – and mercury. Fluorescent lamps contain several types of phosphors: the red phosphor  $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$  (YOX), the green phosphors  $\text{LaPO}_4:\text{Ce}^{3+},\text{Tb}^{3+}$  (LAP),  $(\text{Gd},\text{Mg})\text{B}_5\text{O}_{12}:\text{Ce}^{3+},\text{Tb}^{3+}$  (CBT),  $(\text{Ce},\text{Tb})\text{MgAl}_{11}\text{O}_{19}$  (CAT) and the blue phosphor  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$  (BAM) (Binnemans et al 2013a). At the end of life of a fluorescent lamp, the lamp is collected to recover the toxic mercury and recycle glass and aluminum (Tan et al 2015). This recovery process produces a powder that contains the phosphors, which is usually landfilled. Solvay implemented a recycling route that enables to extract the REEs from this powder. The phosphors can be degraded over time, so the individual REEs are recovered and used to make “new” phosphors.

The LCA in this thesis aims to assess the environmental impacts of recycled YOX. The recycling process is schematically represented by Figure 7A-1. The phosphorous powder is first pre-treated in two treatment steps: residual glass is removed and the old LAP and YOX are “attacked” in order to be able to extract the rare earth elements (REEs) in their original form. The individual REEs are extracted from the REE mix in 5 subsequent separation reactors. The recycled yttrium and europium are then used to make recycled YOX.

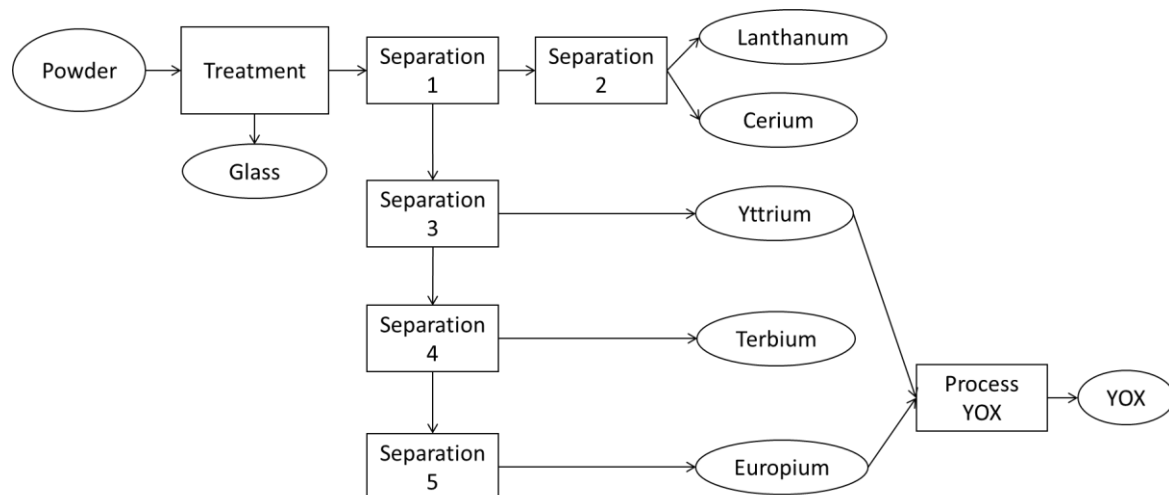


Figure 7A-1 Schematic representation of the production of recycled YOX from valorized phosphorous powder

#### 2.2. The intended audience

The intended audience influences other elements of the goal and scope definition, which subsequently influence the allocation procedures that are applied. The target audiences are decision-makers, who have to decide whether to invest in the recycling route for YOX or not, as well as potential buyers of

recycled YOX. The LCA results will inform them if the use of recycled YOX in their (downstream) products has environmental benefits over the use of primary YOX.

### 2.3. The perspective of the LCA

The systematic framework of Figure 3-10 shows that the perspective of the LCA is one of the elements of the goal and scope that influences the allocation procedure. Two main different perspectives were identified in Chapter 3:

- An attributional LCA assesses for what impacts a product or process is accountable. This is related to choices that are made by upstream and downstream actors that are involved in the life cycle of the product. This type of information can inform both the company that executes the recycling process and the user of the recycled material whether the recycling activity is more environmentally sustainable than the primary production of YOX.
- A consequential LCA calculates the consequences of changes caused by decisions or actions (Zamagni et al 2008). The LCA practitioner applies a consequential approach if it is of interest to know what environmental impacts are caused by the recycling of YOX.

The approaches provide different and complementary information. Therefore, both types of LCA studies are conducted.

### 2.4. The reasons to carry out the LCA

The LCA study of this thesis aims to evaluate the environmental performance of the recycling process. However, it is also aimed to provide background data for further LCA studies, for example on applications that use the recycled YOX as a material input. Therefore, both a process-oriented and a product-oriented LCA are conducted.

### 2.5. The intended application

The following applications are foreseen:

- **Quantifying** the impacts of the recycling process as well as the impacts of recycled YOX for use in other LCA studies or for environmental labeling.
- **Identifying opportunities to improve** the environmental performance of both the recycling process and recycled YOX at various points in their life cycle.
- **Making a decision** between multiple alternative options:
  - *Attributional LCA:*
    - Benchmarking: Can the impacts of recycled YOX be considered high or low?
    - Environmental portfolio management: Is a company that recycles YOX responsible for lower impacts than a company that produces primary YOX?
  - *Consequential LCA:*
    - Global improvements: Is it environmentally beneficial to recycle YOX?

### 2.6. The functional unit and system boundaries

In accordance with the LCA goals described above, the initial functional unit of the LCA studies is set as “1 kg of recycled YOX ready for shipment”. The impacts are assessed from cradle-to-gate. The system boundaries are represented in Figure 7A-2.

### 2.7. Allocation procedures

Figure 7A-2 shows that the valorization process of the phosphorous powder into recycled YOX is a multifunctional process: a waste is disposed of and several co-products are produced. Therefore, an allocation procedure is required. The systematic framework of Figure 3-10 shows that allocation can

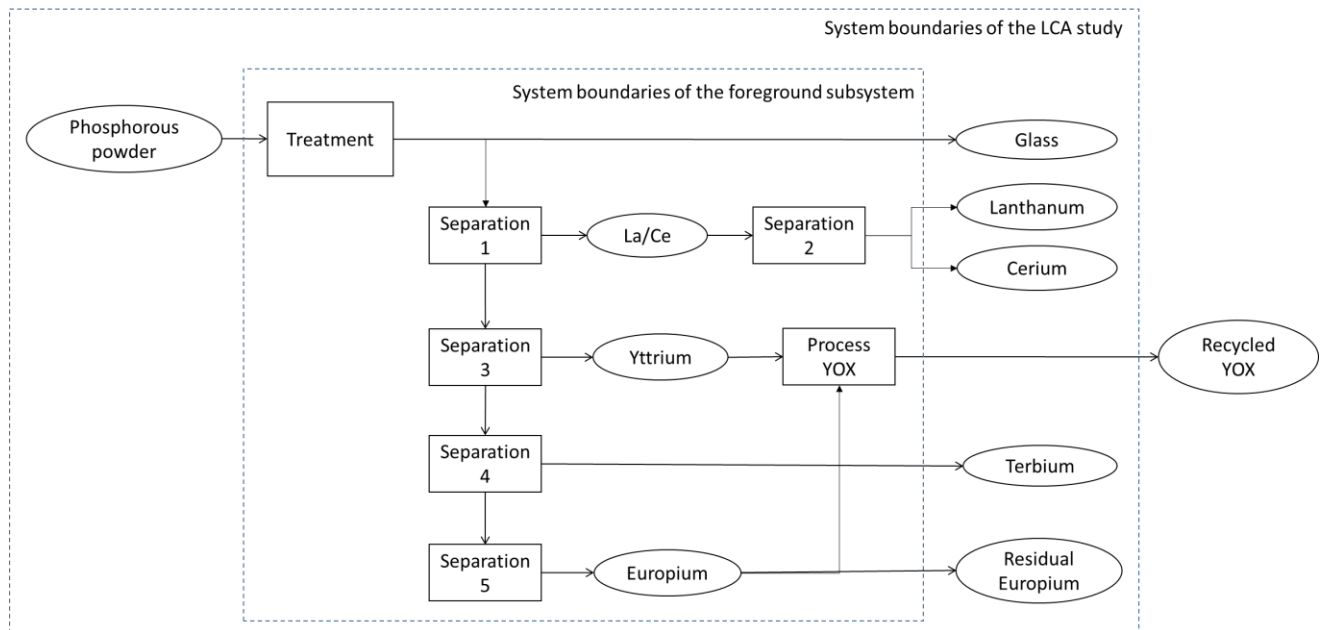


Figure 7A-2 Cradle-to-gate system boundaries for both the process-oriented and product-oriented LCA study with the functional unit of “1 kg of recycled YOX ready for shipment”

be applied by system expansion or partitioning in attributional LCA and substitution in consequential LCA.

#### 2.7.1. System expansion in attributional and consequential LCA

System expansion can be applied in process-oriented LCAs. In an attributional LCA, system expansion avoids the need to apply partitioning, which enables to keep the valorization process as complete as possible. This allows for a full understanding of the process. In a consequential LCA, system expansion can simplify the analysis by avoiding to model the consequences of the co-functions.

The input of the waste and the outputs of the co-products are normalized to the production of 1 kg of YOX in Table 7A-1. The functional unit of the process-oriented LCA now becomes “[the production of] 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of residual recycled europium and [the treatment of] 9.92 kg of phosphorous powder from used fluorescent lamps”. The system boundaries for this extended functional unit are depicted in Figure 7A-3.

#### 2.7.2. Partitioning in attributional LCA

The aim of the product-oriented LCA is to identify what impacts can be attributed to 1 kg of recycled YOX. Partitioning is applied in order to isolate the production of YOX from the other co-functions. The partitioning method “Allocation at the point of substitution” (APOS) is considered as the most suitable allocation procedure to provide an answer to the question for what environmental impacts a product is accountable.

To allocate the impacts of the recycling process between the co-products, it must be identified which material flows are co-products and which flows are intermediate flows that require further treatment, hence, that cannot carry a burden (Axiom 3 and Definition 1 of Chapter 5). Following Axiom 3, the product system that provides the phosphorous powder is responsible for the impacts that take place during its waste treatment. Therefore, part of the recycling process is attributed to the product system of the fluorescent lamp in which the powder is produced. Furthermore, part of the impacts of the product system of the fluorescent lamps is attributed to the recycled YOX.

Table 7A-1 Quantities of waste inputs and product outputs of the recycling process of 1 kg of YOX

Flows	Waste inputs (kg)	Product outputs (kg)
Phosphorous powder	9.92	
Recycled YOX		1
Recycled glass		2.05
Recycled lanthanum		0.18
Recycled cerium		0.14
Recycled terbium		0.07
Recycled europium		0.0029

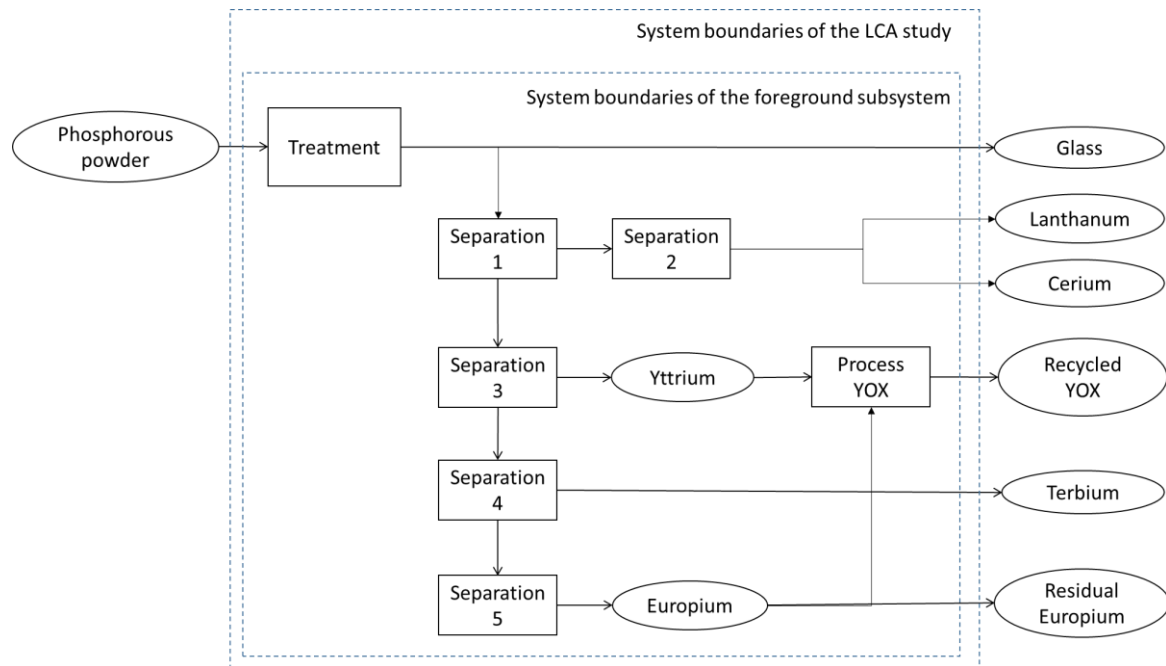


Figure 7A-3 System boundaries of the process-oriented cradle-to-gate LCA with the expanded functional unit of “the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of residual recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps”. It should be noted that the system boundaries of the LCA study are not exactly the same as the system boundaries of the foreground subsystem because other intermediate flows that enter or exit the foreground system (such as electricity or wastes) are omitted from this figure

The application of APOS requires an understanding of the product system of the fluorescent lamp. This additional inventory also enables to do additional analyses on the impacts of the lamp. The additional functional unit of “1 fluorescent lamp” is analyzed in a product-oriented LCA. The impacts of a lamp of which no phosphorous powder is recycled are compared to the impacts of a lamp that valorizes the powder, and to a lamp that also uses recycled YOX as a material input. The cradle-to-grave system boundaries of the product system of the lamp are shown in Figure 7A-4. More details on the definition of these system boundaries are provided in the attributional case study of Chapter 7B. This is an example of the iterative nature of Life Cycle Assessment: during the assessment, the functional unit can be adapted and new types of analyses appear to be interesting. Analyses on the demand for a fluorescent lamp can inform lamp producers whether their participation in the recycling chain is environmentally beneficial. It also informs consumers of lamps whether a lamp that is involved with the recycling process is indeed environmentally preferable over a lamp that is not recycled.

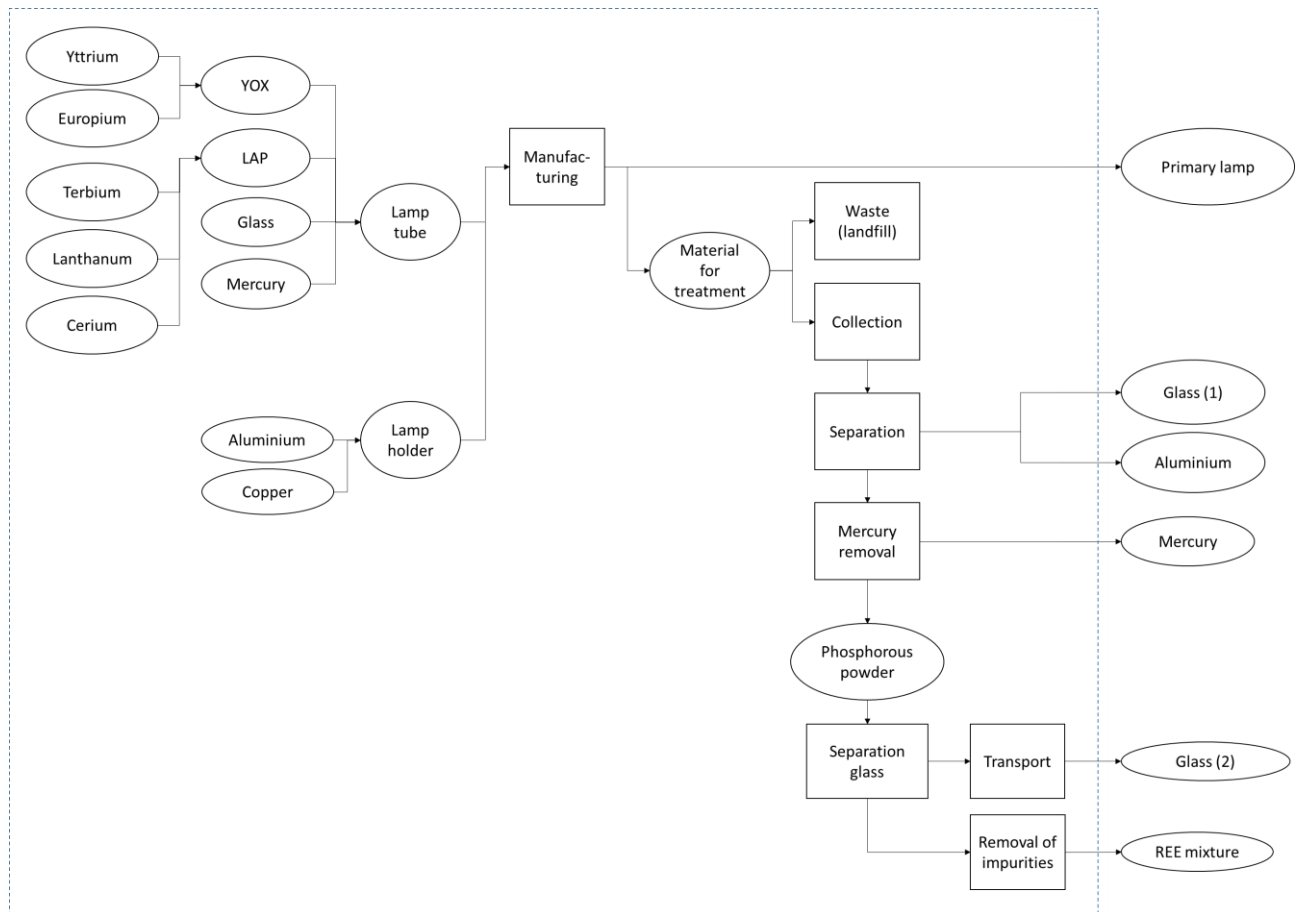


Figure 7A-4 Cradle-to-grave system boundaries of the simplified product system of the fluorescent lamp and its co-products

### 2.7.3. Substitution in consequential LCA

In consequential LCA, the consequences of multifunctionalities are assessed by further modeling of indirect effects – referred to as substitution. This is done with the help of the Causal Loop Diagram (CLD) of Figure 7A-5. The factor  $A$  in the CLD represents the market-price ratio between the valorized product and the substituted alternative – i.e. primary – product.

In the process-oriented LCA, the CLD is not initiated by the changing supply or demand of a product, but by a changing production of a process. The recycling process is represented by the “valorization” box in the CLD. The process-oriented LCA analyses the consequences related to an increased valorization of an intermediate flow. Three types of consequences were identified, which are represented by three arrows exiting the “valorization” box. Only the arrows that are not represented by the functional unit are assessed. Therefore, system expansion allowed to decrease the number of consequences that is assessed in the LCA: the functional inputs (wastes) and outputs (co-products) are included in the functional unit. However, the consequences of the avoided waste treatment of the phosphorous powder and the co-production of glass and other REEs are of interest as well, which is why the functional unit of “1 kg of recycled YOX” is also analyzed in a process-oriented LCA.

In the product-oriented LCA, the demand for recycled YOX is analyzed. In the CLD, “demand product” is now the starting point of the analysis. No downstream effects are modeled in this cradle-to-gate LCA. During the attributional LCA on recycled YOX, inventory of the life cycle of a fluorescent lamp is modeled. This inventory allows for an additional consequential assessment as well. The demand for a fluorescent lamp is also modeled by “demand product”. The additional production of a lamp automatically results in the production of a product that requires waste treatment. Hence, the demand

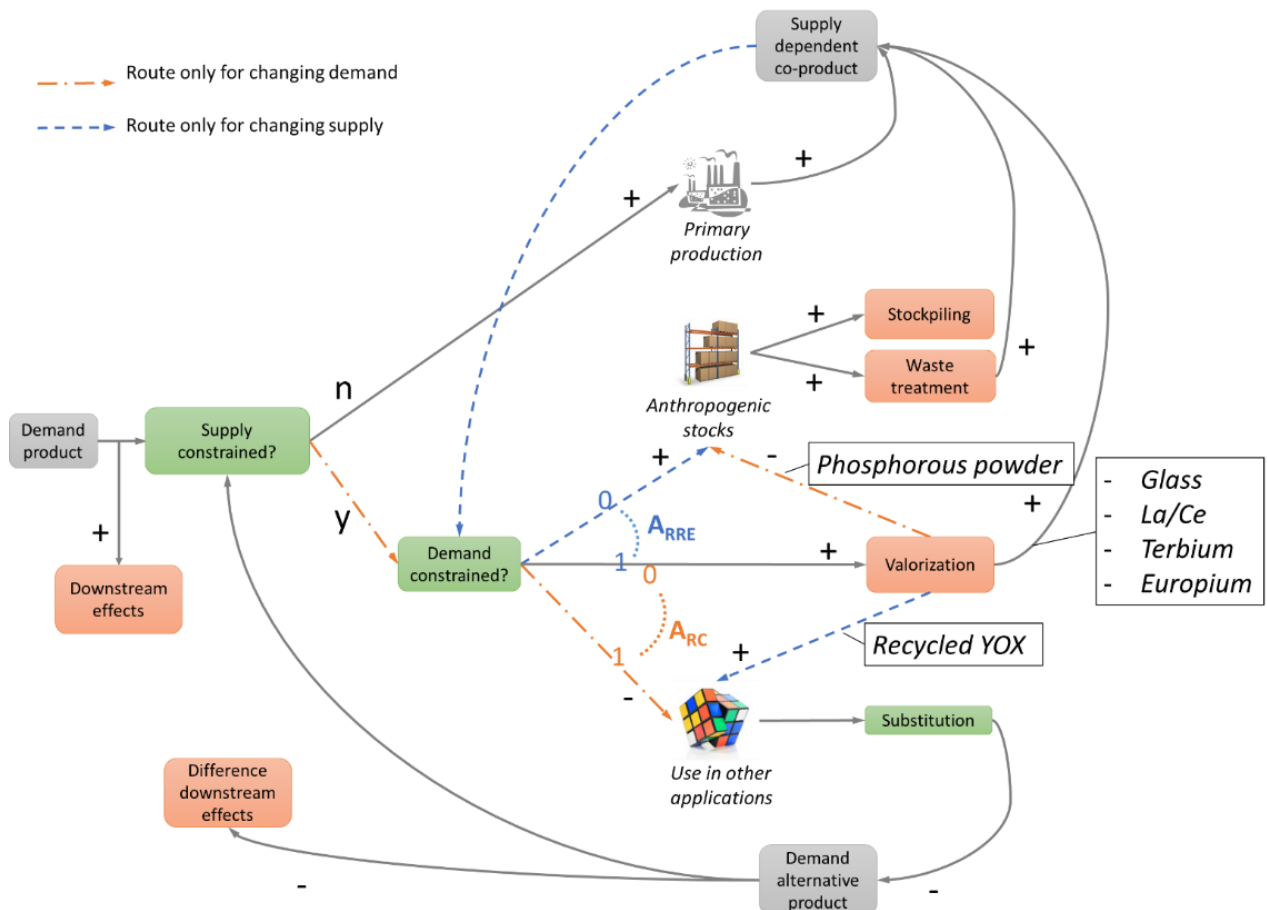


Figure 7A-5 Assessment of the production of recycled YOX from phosphorous powder in the Causal Loop Diagram

for a fluorescent lamp leads to “supply dependent co-product” of the end-of-life lamp. The consequences of this supply are modeled by the CLD as well.

## 2.8. Data sources

Data for the foreground system – which refers to processes operated by Solvay – is provided by Lartigue-Peyrou (2016). Intermediate flows that enter the foreground system must be modeled from cradle to gate, and intermediate flows that exit the foreground system must be modeled from gate to grave, i.e. waste treatment. Several databases for background data exist that could be used to model the cradle to gate of intermediate inputs and gate to grave of intermediate outputs. ecoinvent is one of the databases that is most often used.

### 2.8.1. Attributional background database

ecoinvent 3.2 proposes two system models – i.e. two different configurations of the database – that could be used in an attributional LCA. One of the main differences in different background databases is the allocation procedure that is applied to upstream co-products. In the APOS system model – previously called “Allocation, ecoinvent default” –, the same allocation procedure is applied as in the foreground system. For a consistent study, the allocation procedure that is applied to the foreground system is the same as the procedure that is implemented in the background database. This is also a requirement in ISO 14044: “Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system.” The APOS system model is therefore identified to be most suitable to provide background data for the attributional case study.

### 2.8.2. Consequential background database

The consequential system model of the ecoinvent 3.2 database is used for the consequential case study. This system model provides us with information on what impacts are caused by extracting or delivering one more unit of this intermediate flow from or to the technosphere. Not only is this the only consequential background database available at the moment, this consequential database is suitable for this LCA study because a similar scope is applied: the system model represents the consequences of small-scale (i.e. marginal), long-term decisions (Weidema et al 2013).

### 2.8.3. Additional data sources

Some data is not available in ecoinvent, such as the primary production of rare earth elements from ionic ore deposits. Other data is available in ecoinvent, while the modeling does not entirely correspond to the allocation procedure applied in the case study – i.e. the APOS method in attributional LCA and the consideration of constraints of supply and demand in consequential LCA. This is, for example, the case for the primary production of REEs from bastnaesite deposits and the co-production of ammonium sulfate. Primary routes for REEs are modeled by data from scientific literature (Sprecher et al 2014; Vahidi et al 2016) and the attributional inventory for ammonium sulfate is calculated in Annex A (i.e. the case study on the production of polyamide 6). Other missing data is used from literature as well, such as the production and waste treatment of a fluorescent lamp (Tan et al 2015).

## 2.9. Limitations

The LCA represents as much as possible current operations. This requires up-to-date data. Of course, the analysis is limited to the data availability corresponding to this scope. The main purpose of this chapter is to demonstrate the application of the attributional and consequential approach and the allocation procedures. Therefore, crude but reasonable assumptions in the case of lacking data are considered acceptable.

### *Limitations specific for the consequential LCA*

The LCA aims to inform decision-makers on investment options based on the current market situation and currently available production technologies of the relevant materials and processes in the product system, with their current level of performance. Therefore, the consequences of interest take place in the long term (Frischknecht 1998; Weidema et al 2009).

We apply the *ceteris paribus* assumption, which implies that the demand for the functions of other products in the market is unchanged. This means that only the substitution effects of co-production and recycling are included in the analysis, while additional rebound effects, for example, due to differences in prices of the products, are not considered.

It is assumed that the consequences of the functional unit are marginal, i.e. they do not influence the determining parameters of the product markets (Weidema et al 2009). The LCA represents as much as possible current operations. This requires up to date data and market prices for the identification of the determining co-product of each process. Of course, the analysis is limited to the data availability corresponding to this scope. The main purpose of this chapter is to demonstrate the application of the consequential approach and the allocation procedures. Therefore, crude but reasonable assumptions in the case of lacking data are considered acceptable.

## 2.10. Impact assessment method

The impact assessment is done in Simapro 8.2.3.0 with the impact assessment method ILCD 2011 Midpoint+ v 1.08. This method is a compilation of various characterization methods from different impact assessment methods that are recommended by the European Commission (European



Commission 2012). Recommendations are based on several scientific criteria (completeness of scope, environmental relevance, scientific robustness and certainty, documentation, transparency, reproducibility and applicability) as well as the degree of stakeholder acceptance and suitability for communication in a business and policy context. Furthermore, additional criteria were developed for each impact category. For example, one of the additional criteria for climate change is the consideration of atmospheric fate and transport (European Commission 2011b). The fact that the suitability for communication of the impact results is considered as one of the selection criteria makes this compilation of impact assessment methods suitable for this case study.

The impact categories that are investigated are climate change, ozone depletion, human toxicity (cancer effects and non-cancer effects), particulate matter, ionizing radiation (human health and ecosystems), photochemical ozone formation, acidification, terrestrial, freshwater and marine eutrophication, freshwater ecotoxicity, land use, water resource depletion and mineral, fossil and renewable resource depletion.

### 3. Conclusions

This chapter presents the goal and scope of the case study on the recycling of rare earth elements of end-of-life fluorescent lamps. The goal and scope definition contains elements that influence the allocation procedure that is applied in the case study. The systematic framework of Chapter 3 has been applied to identify the appropriate allocation procedure, based on these elements.

First, the systematic framework of Chapter 3 has been updated with the partitioning method APOS (Chapter 5) and the market-driven substitution method of Chapter 6. The goal and scope of the current chapter formulated the need for both an attributional and a consequential LCA. Furthermore, both a product-oriented and process-oriented LCA will be conducted. The relevant parameters that influence the LCA approach are summarized in Table 7A-2. From these parameters, archetypical goal and scope definitions can be formulated. These archetypical LCAs are conducted in the attributional case study of Chapter 7B and the consequential case study of Chapter 7C.

Table 7A-2 Summary of parameters that contribute to archetypical LCA studies

Item of the goal and scope definition	LCA approach	Building blocks of archetypical goal and scope definitions	
The perspective of the LCA	Attributional LCA	$\alpha$	$\alpha$ : Accountability for impacts
	Consequential LCA		$\alpha$ : Consequences on global impacts
The reason to conduct the study	Process-oriented LCA	$\beta$	$\beta$ : The production / treatment
	Product-oriented LCA		$\beta$ : The demand
The functional unit	Partitioning / Substitution	$\gamma$	$\gamma$ : 1 kg of recycled YOX ready for shipment $\gamma$ : 1 fluorescent lamp
	System expansion		$\gamma$ : 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of residual recycled europium and 9.92 kg of phosphorous powder from used fluorescent lamps

## Chapter 7B: Attributional LCA on the recycling of rare earth elements from end-of-life fluorescent lamps

### 1. Introduction

In this thesis, it has been shown that recycling can be modeled in an attributional LCA by applying system expansion or partitioning. Although partitioning is often applied to co-production, this is not often done in LCA studies, in which recycling takes place. In Chapter 5, we identified a partitioning approach that is equally applicable to recycling and co-production. This chapter applies allocation at the point of substitution in an attributional case study of recycled phosphors from fluorescent lamps. The same recycling process is the topic of a consequential case study in Chapter 7C. The case studies illustrate how the allocation procedures can be applied and how the results can be interpreted.

The goal and scope of the LCA have been formulated in Chapter 7A. From Chapter 7A, key parameters were identified from the goal and scope that represent archetypical LCA studies. These parameters are summarized in Table 7B-1. From the building blocks of archetypical goal and scope definitions, a set of research questions is developed, which form the basis of the attributional LCA study of this chapter.

### 2. Archetypes of attributional LCA goal and scope definitions

In Section 3.3 of Chapter 3, it was illustrated how the elements of the goal and scope definition can result in archetypical LCA studies. These archetypes – that are represented in the text box – capture the main differences that influence the allocation procedure, based on the perspective of the LCA, the reason to carry out the study and the functional unit. Each research question refers to a different intended application of the LCA, i.e. quantifying impacts, identifying options for improvement or decision-making.

Table 7B-1 Summary of parameters that contribute to archetypical attributional LCA studies. The terms represented by  $\alpha$ ,  $\beta$ , and  $\gamma$  are used in the archetypical goal and scope definitions as defined in the box below

Item of the goal and scope definition	LCA approach	Building blocks of archetypical goal and scope definitions	
The perspective of the LCA	Attributional LCA	$\alpha$	$\alpha$ : Accountability for impacts
The reason to conduct the study	Process-oriented LCA	$\beta$	$\beta$ : The production / treatment
	Product-oriented LCA		$\beta$ : The demand
The functional unit	Partitioning	$\gamma$	$\gamma$ : 1 kg of recycled YOX ready for shipment $\gamma$ : 1 fluorescent lamp
	System expansion		$\gamma$ : 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of residual recycled europium and 9.92 kg of phosphorous powder from used fluorescent lamps

### Archetypical attributional LCA goal and scope definitions

- **Quantifying environmental impacts:**
  - What is/are the  $\alpha$  of  $\beta$  of/for  $\gamma$ ?
- **Identifying opportunities for improvement:**
  - How can we decrease the impacts of  $\beta$  of/for  $\gamma$ , in order to decrease the  $\alpha$ ?
- **Decision-making:**
  - *Benchmarking*: Does  $\beta$  of/for  $\gamma$  have (a) lower  $\alpha$  than its alternative?
  - *Environmental portfolio management*: Is [stakeholder] accountable for lower impacts due to the  $\beta$  of/for  $\gamma$  than in an alternative situation?

Note that there is no relevant difference between benchmarking and environmental portfolio management in a product-oriented LCA. The archetypes of attributional LCA goal and scope definitions can now be expressed in the form of the following research questions. These research questions are slightly rewritten compared to the questions in the box to increase readability:

- Process-oriented LCA:
  - For what environmental impacts are the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps accountable?
  - How can we reduce the environmental impacts of the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps, in order to reduce its accountability for impacts?
  - Is the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps less accountable for environmental impacts than alternative production and treatment processes of these products?
  - Is a company accountable for lower impacts due to the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps than due to the production of primary REEs?
- Product-oriented LCA on 1 kg of recycled YOX:
  - For what environmental impacts is the demand for 1 kg of recycled YOX accountable?
  - How can we decrease the impact of the demand for 1 kg of recycled YOX, in order to reduce its accountability for impacts?
  - Is the demand for 1 kg of recycled YOX less accountable for impacts than the demand for 1 kg of primary YOX?
- Product-oriented LCA on 1 fluorescent lamp:
  - For what environmental impacts is the demand for 1 fluorescent lamp accountable?
  - How can we decrease the impact of the demand for 1 fluorescent lamp, in order to reduce its accountability for impacts?
  - Which of the following lamps is accountable for lower impacts?
    - 1 fluorescent lamp that is not involved with the valorization process,

- 1 fluorescent lamp that only valorizes the phosphorous powder at the end of life, or
- 1 fluorescent lamp that contains recycled YOX and valorizes the phosphorous powder at the end of life
- Is the demand for 1 fluorescent lamp with a high content of recycled YOX less accountable for impacts than the demand for 1 fluorescent lamp that contains a low content of recycled YOX?

### 3. Inventory analysis

In this section, the collection of inventory is described that corresponds to the LCA goal and scope definition. It is also demonstrated how the inventory is applied to the product-oriented equations of Chapter 5.

#### 3.1. Process-oriented LCA

System expansion is applied in the process-oriented LCA. Elementary flows were collected for the foreground system, and intermediate flows are modeled with the ecoinvent 3 APOS system model. This had provided sufficient information for the quantification of impacts of the recycling process and for the identification of options for improvement. However, for decision-making – where a comparison is done with an alternative product system via benchmarking or to support environmental portfolio management – additional inventory is required.

##### 3.1.1. Benchmarking

Benchmarking can be done to indicate whether the impacts of the valorization process of recycled YOX are high or low. We compare the recycled YOX with the average production route of YOX, which is generally from primary resources. However, for this comparison, it is important that the alternative production route of YOX provides the same functions as the valorization process for recycled YOX. Therefore, the expanded functional unit is also used for the alternative product system. For each function of Table 7B-1 an alternative production or treatment route should be identified. The alternative product system is represented in Figure 7B-1.

##### 3.1.1.1. Waste treatment of phosphorous powder

In general, the phosphorous powder is not recycled but sent to landfill. This is modeled by a standard process in ecoinvent 3 for the landfilling of hazardous waste.

##### 3.1.1.2. Production of recycled glass

It is tempting to assume that the recycled glass has the same properties as primary glass. In that case, the alternative production route is the primary production of glass. However, insights from the consequential methodology described in Chapter 6 can be applied to identify whether the recycled glass is fully comparable to primary glass. This comparison is further specified in the consequential study of Chapter 7C. Recycled glass cullet (after transport) has a market price of 7% of the market price of primary glass. In this chapter, the same assumption is done as in Chapter 7C: recycled glass can displace only 7% of the primary production process of glass. Therefore, the function related to the production of recycled glass is considered to be comparable to 7% of the production of primary glass. Transport is modeled in the recycling system based on an adapted ecoinvent dataset that refers to the transport of recycled glass.

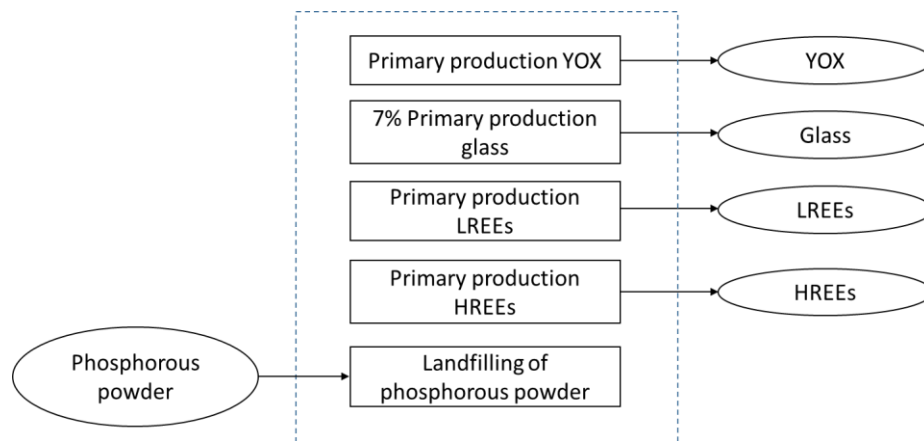


Figure 7B-1 Alternative product system for the recycling process of YOX for the purpose of benchmarking. Light REEs (LREE) are lanthanum, cerium and residual europium. Heavy REEs refers to the recycled terbium

#### 3.1.1.3. Production of recycled YOX

The recycled YOX provides the same function as primary YOX and can be used in the same applications, without negative downstream effects. Therefore, the primary production route of YOX is considered as a comparable alternative. It is assumed that the (slight) difference in the market prices is related to the general image of recycled materials.

#### 3.1.1.4. Production of other recycled REEs

All the other rare earth elements that are produced during the recycling process show similar properties as their primary rare earth oxide (REO) equivalent. Therefore, primary REOs are considered as comparable functional outputs. Although most REEs are produced from bastnäsite deposits of the Bayan Obo mine in China, this mine mostly contains light rare earth elements (LREE), and to a much lower extent heavy REEs (HREE), such as terbium and – often also considered as an HREE – yttrium. HREEs are mined via a different production route, mostly via ionic ore mining in China. Therefore, the primary production of the REOs is modeled via two different routes. Primary REOs are always produced in co-production; often of other minerals, and always as co-product of each other. Therefore, REOs always undergo a separation process. There are several techniques to separate REOs, although it is most often done by solvent extraction (Gupta and Krishnamurthy 2005). The order of separation is mainly based on the small differences in basicity due to the different ionic radii of the elements, as depicted in Figure 7B-2 (Gupta and Krishnamurthy 2005). Allocation is applied in the primary production routes to identify for what impacts of the primary production route each REO can be held accountable.

##### 3.1.1.4.1. Allocation of primary REEs

In Chapter 3, the difference between combined production and joint production was introduced: in combined production, the ratio of the co-products can be adjusted, while in joint production the production ratio is fixed. The separation process of REEs contains elements of both combined and joint production.

An example for combined production is the combined separation of rare earth elements from different mines. Each mine provides a rare earth concentrate of a different composition. The separation process is optimized for the mixed composition of the different RE concentrates. This is a typical example of a multifunctionality situation that could be solved by modeling based on physical relationships, such as the marginal allocation approach of Azapagic & Clift (1999). In that case, different datasets of the separation process could be generated for each source material. Ideally, a parametrized model would be developed that would adjust the inventory of the separation process based on the composition of

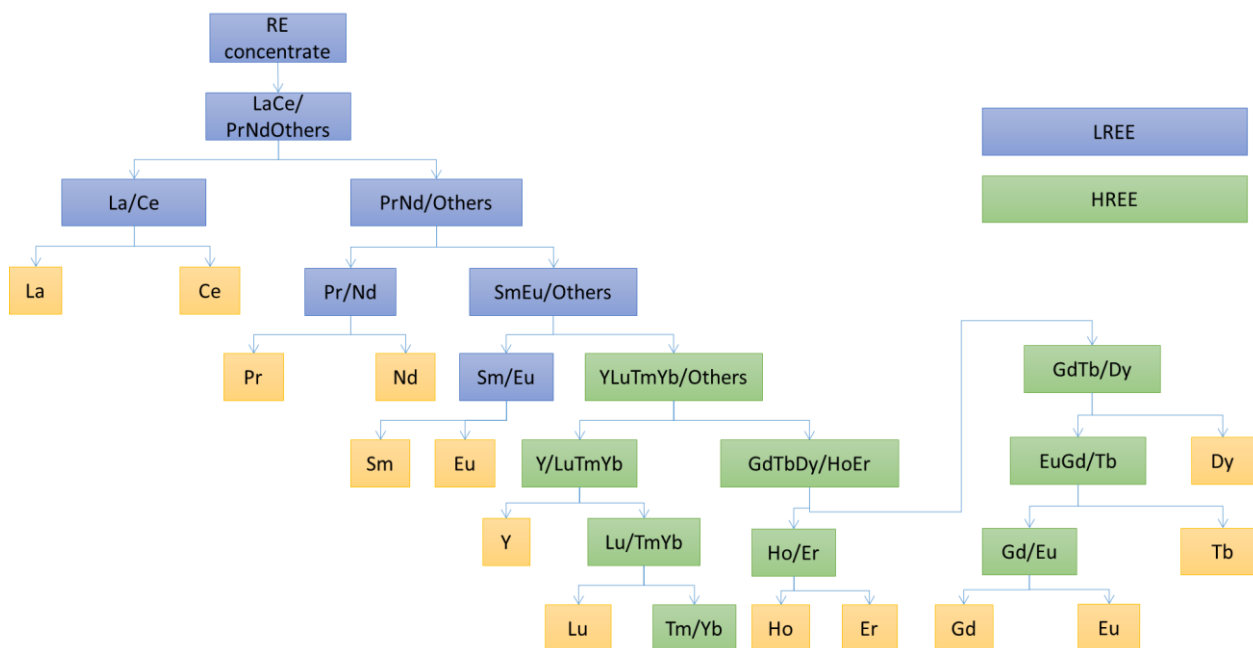


Figure 7B-2 Separation process of REEs (Lévêque and Maestro 1993; Wang et al 2013). The content of the REE mix determines whether the emphasis is put on the LREE or the HREE separation route

the RE concentrate. However, such an analysis is outside the scope of this study. In this LCA, very simplistic assumptions are done with regard to the separation process of REEs from one single mine.

Although the combined separation of RE concentrates of different deposits is a combined production process, the separation of a REE mix of one deposit is a joint production process. The ratio in which the outputs are produced is fixed by the ratio in which they appear in the inputs. Therefore, allocation based on physical relationships is not applicable to the co-produced REEs from a single mine. APOS is applied to identify the accountability for impacts of an individual REEs, based on the relative revenue of each REE. The choice for economic partitioning in the specific case of REEs is discussed in Annex II.

#### 3.1.1.4.2. Primary production of light REEs

In ecoinvent, the primary production of rare earth elements is modeled as depicted in Figure 7B-3. Cerium concentrate, lanthanum oxide, neodymium oxide, praseodymium oxide and samarium europium gadolinium concentrate are all considered as co-products from the separation process of rare earth concentrate from bastnäsite, which is modeled as the single output of a mining activity. Although these flows are available in the APOS system model of ecoinvent, this representation of the rare earth production process is not fully in line with “allocation at the point of substitution” as described in Chapter 5. Rare earth concentrate from bastnäsite is mainly produced as a by-product from iron mining in China (Gupta and Krishnamurthy 2005). Therefore, it should be expected that “rare earth concentrate” or rare earth oxide (REO) ore is modeled as a co-product from an activity that produces iron ore as a co-product as well.

Furthermore, the “point of substitution” of both the REO ore as well as the REOs during or after the separation step is debatable. Due to the fact that REO ore is not always produced as a by-product of other materials, REO ore is considered as a co-product at the point of substitution – regardless of the relative concentration of each individual REO within the ore. In ecoinvent, “samarium europium gadolinium concentrate” (SEG-C) is considered as a co-product, at the same level as the co-products cerium concentrate, lanthanum oxide, praseodymium oxide and neodymium oxide. SEG-C is now held accountable for part of the separation activities that were required to extract cerium, lanthanum,

neodymium and praseodymium. However, these separated elements will not be held accountable for the further separation steps that are necessary to extract samarium, europium, and gadolinium. It is difficult to identify the point of substitution of a primary product that is always produced in co-production. As stated before, there are several possible separation techniques for REEs. The choice of solvent and the extraction route can be influenced by the expected revenue of the REEs in the mix (Gupta and Krishnamurthy 2005). This makes it complicated to identify a combination of specific REEs as a co-product of the production process. Therefore, the point of substitution is identified at the production of the individual REEs and the datasets for primary rare earth elements in ecoinvent 3 are not considered suitable for this specific LCA study.

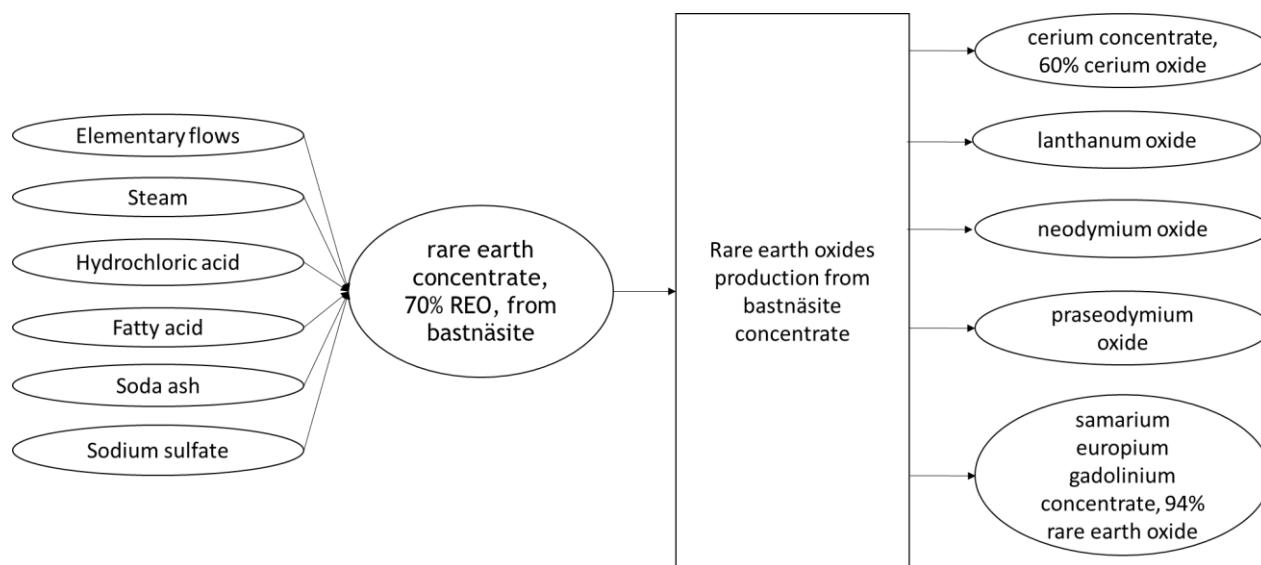


Figure 7B-3 Primary production route of REOs from bastnäsite, as modeled in ecoinvent 3.2

More detailed inventory for the primary production of REOs from bastnäsite has been developed by Sprecher et al. (2014). This inventory allows to allocate mining between iron ore and REO ore and to allocate the impacts of the separation process equally between all the separated REEs. The allocation factors are presented in Table 7B-2 and Table 7B-3. However, it should be noted that it is unclear whether the inventory of Sprecher et al. represents the separation process up to the extraction of the individual elements. For simplicity, it is assumed that this is the case. This might result in an underestimation of the impacts related to the separation process.

Table 7B-2 Calculation of allocation factors of the co-products from iron mining, based on the operations of the Bayan Obo deposit in China

	Yield from 30 kg of mixed ore (kg) <sup>a</sup>	Market price (2013) (USD/kg)	Allocation factor
Iron ore (65% fe)	12.5	\$ 0.14 <sup>b</sup>	> 80%
REO ore (61% REO)	1	\$ < 0.42 <sup>c</sup>	< 20%
Total			100%

<sup>a</sup>Based on Sprecher et al. (2014)

<sup>b</sup>Monthly average of iron ore (62%) 2013 (IndexMundi 2016)

<sup>c</sup>Based on the information that the REO ore is a by-product, i.e. its revenue is not required for the system to operate. The revenue for the REO is therefore estimated to be < 20% of the total revenue (Consequential-LCA 2015a)

Table 7B-3 Calculation of allocation factors of the co-products from REE production from bastnäsite, based on the REE composition of the Bayan Obo deposit in China

	Yield from 1 kg of REO <sup>a</sup> (kg)	Market price (2013) <sup>b</sup> (USD/kg)	Allocation factor
Cerium	0.49	\$ 7.86	15.72%
Lanthanum	0.28	\$ 7.87	9.01%
Neodymium	0.15	\$ 71.80	44.97%
Praseodymium	0.05	\$ 91.40	18.85%
Europium	0.0002	\$ 1,095.00	10.25%
Gadolinium	0.01	\$ 24.00	0.57%
Samarium	0.01	\$ 13.30	0.63%
Total	1.00		100%

<sup>a</sup>Based on Sprecher et al. (2014)

<sup>b</sup>(Statista 2016a)

#### 3.1.1.4.3. Primary production of heavy REEs

For the primary production route of heavy rare earths, inventory is based on the publication of Vahidi, Navarro, & Zhao (2016). This inventory describes the extraction up to the separation step. Therefore, the separation process must be modeled separately. As a simplification, it is assumed that the separation by solvent extraction of HREE is similar to solvent extraction of LREE from bastnäsite. The solvent extraction is therefore modeled by the inventory developed by Sprecher et al. (2014). It should be noted that this is highly uncertain, due to the different composition of the REEs. Furthermore, the inventory of Vahidi et al. does not take the consumption of the individual rare earths from the earth's crust into account. These have been added under the assumption that all the REEs are recovered. In this chapter, we use the Longnang deposit in the Jiangxi province in China as a representative mine for HREE (Brumme 2014). The allocation factors are given in Table 7B-4. During the mining process, ammonium sulfate is used. Ammonium sulfate is a co-product of caprolactam (see Annex A). Ecoinvent 3 contains a dataset for ammonium sulfate. However, this dataset does not contain upstream data related to the production of caprolactam. Therefore, the dataset is not compliant with the APOS method. In Annex A, allocation is applied by APOS between caprolactam and ammonium sulfate. Therefore, the data from the case study in Annex A is used to represent the inventory of ammonium sulfate used during the mining process.

#### 3.1.2. Environmental portfolio management

If a producer of REEs decides to produce more YOX via the recycling process than via the primary production process, this company might be interested in knowing how its environmental portfolio changes: whether the company is accountable for higher or lower environmental impacts when recycling takes place. In this analysis, the alternative route only contains processes for which the company under study could already be accountable, as they already existed in the supply chain of this company (Figure 7B-4). Therefore the primary production routes are not necessarily modeled as average processes, but as processes that the stakeholder chooses to replace by the recycling process. Note that in this analysis the two production routes do not provide the same functions.



Table 7B-4 Calculation of allocation factors of the co-products from REE production from ionic ore, based on the REE composition of the Longnan deposit in China

	Yield from 1 kg of REO <sup>a</sup>	Market price (2013) <sup>b</sup>	Allocation factor
Yttrium	0.65	\$ 26.00	20.36%
Lanthanum	0.0182	\$ 7.87	0.17%
Cerium	0.004	\$ 7.86	0.04%
Praseodymium	0.007	\$ 91.40	0.77%
Neodymium	0.03	\$ 71.80	2.59%
Samarium	0.028	\$ 13.30	0.45%
Europium	0.001	\$ 1,095.00	1.32%
Gadolinium	0.069	\$ 24.00	1.99%
Terbium	0.013	\$ 920.00	14.41%
Dysprosium	0.067	\$ 555.00	44.79%
Holmium	0.016	\$ 66.00	1.27%
Erbium	0.049	\$ 68.00	4.01%
Thulium	0.007	\$ 53.00	0.45%
Ytterbium	0.025	\$ 53.00	1.60%
Lutetium	0.004	\$ 1,201.00	5.79%
Total	1.00		1.00

<sup>a</sup>(USGS 2015)

<sup>b</sup>(Statista 2016a)

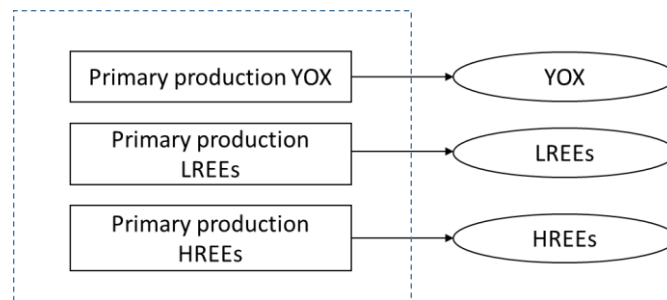


Figure 7B-4 Alternative product system for the recycling process of YOX for the purpose of environmental portfolio management

### 3.2. Product-oriented LCA

Partitioning is applied in the product-oriented LCAs. The procedure contains the following phases (see Chapter 5):

1. Identifying the co-products of the recycling process
2. Identifying the product system that produces the waste
3. Rearranging the system boundaries
4. Applying “allocation at the point of substitution”

#### 3.2.1. Identifying the co-products of the recycling process

In this section, we apply the reasoning that was developed in Chapter 5 to the recycling process of YOX as depicted in Figure 7A-1. Is recycled YOX responsible for the separation of lanthanum and cerium by “Separation 2”? Is the recycled lanthanum responsible for “Process YOX”? To answer this, it is determined below which flows are intermediate processing flows or wastes, and which flows are actual co-products.

### 3.2.1.1. Recycled glass

In one of the first processing steps, some remaining glass is removed from the powder. This glass can be further recycled by conventional recycling routes of glass from used lamps. Recycled glass could be considered a co-product from the point where it can substitute a flow from a primary glass production route, here assumed after transportation to a glass production facility. In this analysis, it is not important which flow is actually substituted. For example, this could be primary glass or primary raw materials such as sand, limestone or even the consumption of electricity.

### 3.2.1.2. Mixture of recycled REEs

After the removal of glass, some treatment steps are applied to remove other impurities related to the function of the lamp. The point of substitution is identified at the point where the mix of rare earth elements is ready to enter the separation reactors. This REE mix is considered comparable to the mixture of primary REEs after leaching and before solvent extraction (Sprecher et al 2014).

### 3.2.1.3. Individual recycled REEs

Separation takes place in several reactors that each extract a different element. It was deliberated before that the intermediate flows between the reactors are not considered as co-products. The individual REEs can, after separation, substitute primary REEs. Therefore, these elements are considered as co-products from the separation process. The intermediate flows that are considered to be co-products in the foreground system are depicted in yellow in Figure 7B-5. The individual recycled rare earth elements are jointly responsible for the cradle-to-gate impacts of the mixture of REEs and all separation steps.

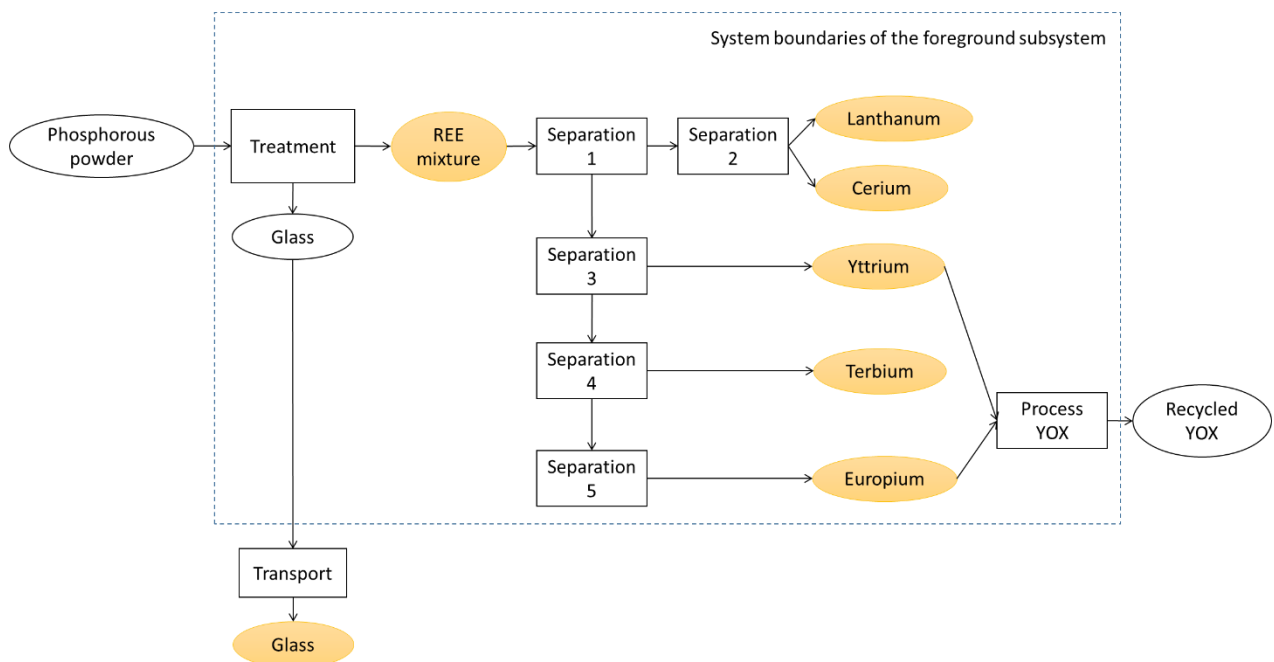


Figure 7B-5 Identification of the co-products of the foreground subsystem (in yellow)

### 3.2.2. Identifying the product system that produces the waste

From Figure 7B-5, it could be concluded that recycled glass and the mixture of REEs are considered to be the first co-products within the foreground process. Considering that one of the intermediate input flows – the phosphorous powder – is a waste, the co-products “Glass” and “REE mixture” are in fact co-products of the product system that produces the phosphorous powder as a waste, i.e. the fluorescent lamp. This complicates the analysis, as more data collection is needed. The inventory of the life cycle of the lamp must be known, as well as all co-products and recycled products that are

produced during this life cycle. A more detailed representation of the system boundaries of Figure 7A-2 is given in Figure 7B-6. The background sub-system is represented in the same style as Figure 3-11 of Chapter 3, to show the context elements that are relevant in the product-oriented LCA.

The life cycle of the lamp could be split into the following life cycle stages (Figure 7B-7): manufacturing, distribution, use and end of life (Tan et al 2015). The fluorescent lamps used here as an example (Linear Fluorescent Lamps (LFL)) are made of a lamp holder and a lamp tube. At the end of life, ideally, all lamps are collected and sent to a dedicated waste treatment facility, where the mercury can safely be removed. Of course, it is possible that some lamps are not correctly collected but treated with normal household waste. At the separation facility, aluminum, glass cullet, and mercury are recovered from the used lamps and recycled. The quantities in Figure 7B-7 refer to the treatment of 350 ton of lamps (Tan et al 2015). Based on the inventory for the production of 10,000 lamps from Tan et al., it could be derived that this waste treatment refers to the treatment of 3.4 million lamps.

The recycled glass and the mixture of REEs from Figure 7B-5 are not necessarily responsible for impacts of all stages of the life cycle of the fluorescent lamp. Following Axiom 1: *All co-products are responsible for cradle-to-gate and gate-to-grave impacts of flows that are used and produced during the co-producing activity*, we should determine which activities in the product system of the lamp are actually co-producing activities. We use similar reasoning as in Chapter 5 to eliminate the irrelevant life cycle stages.

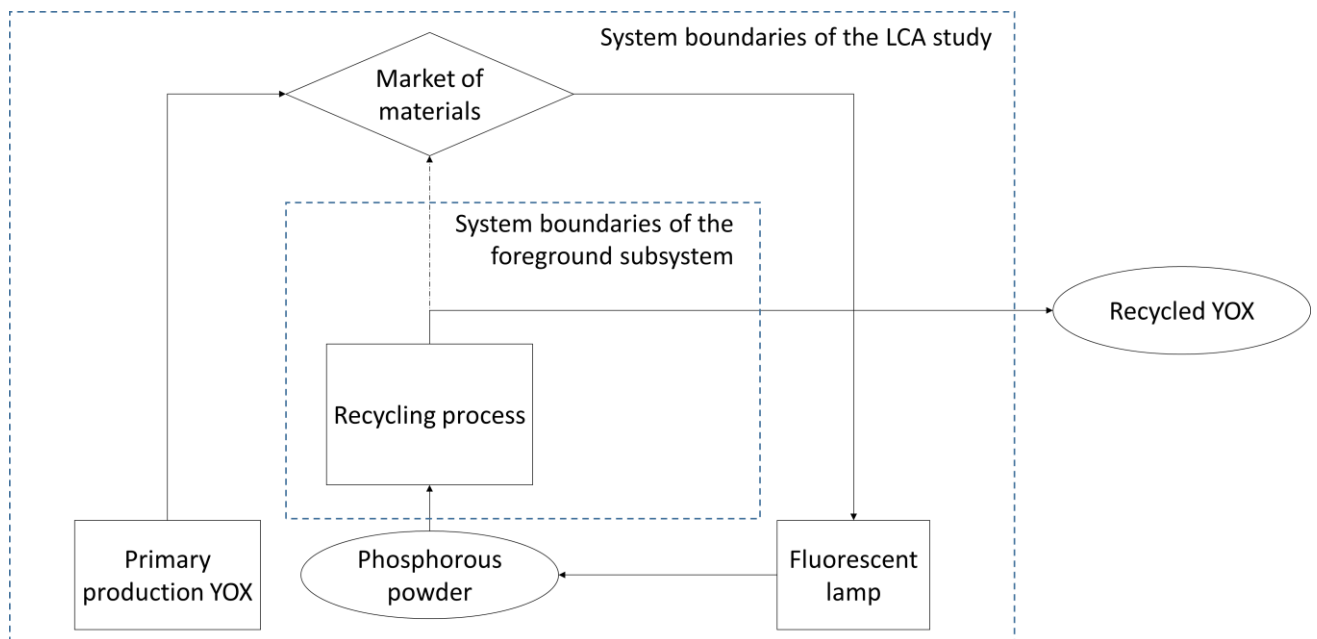


Figure 7B-6 Cradle-to-gate system boundaries of the product-oriented LCA with the functional unit of 1 kg of recycled YOX. The dashed arrow shows the diverted flow of recycled YOX due to the demand of the functional unit

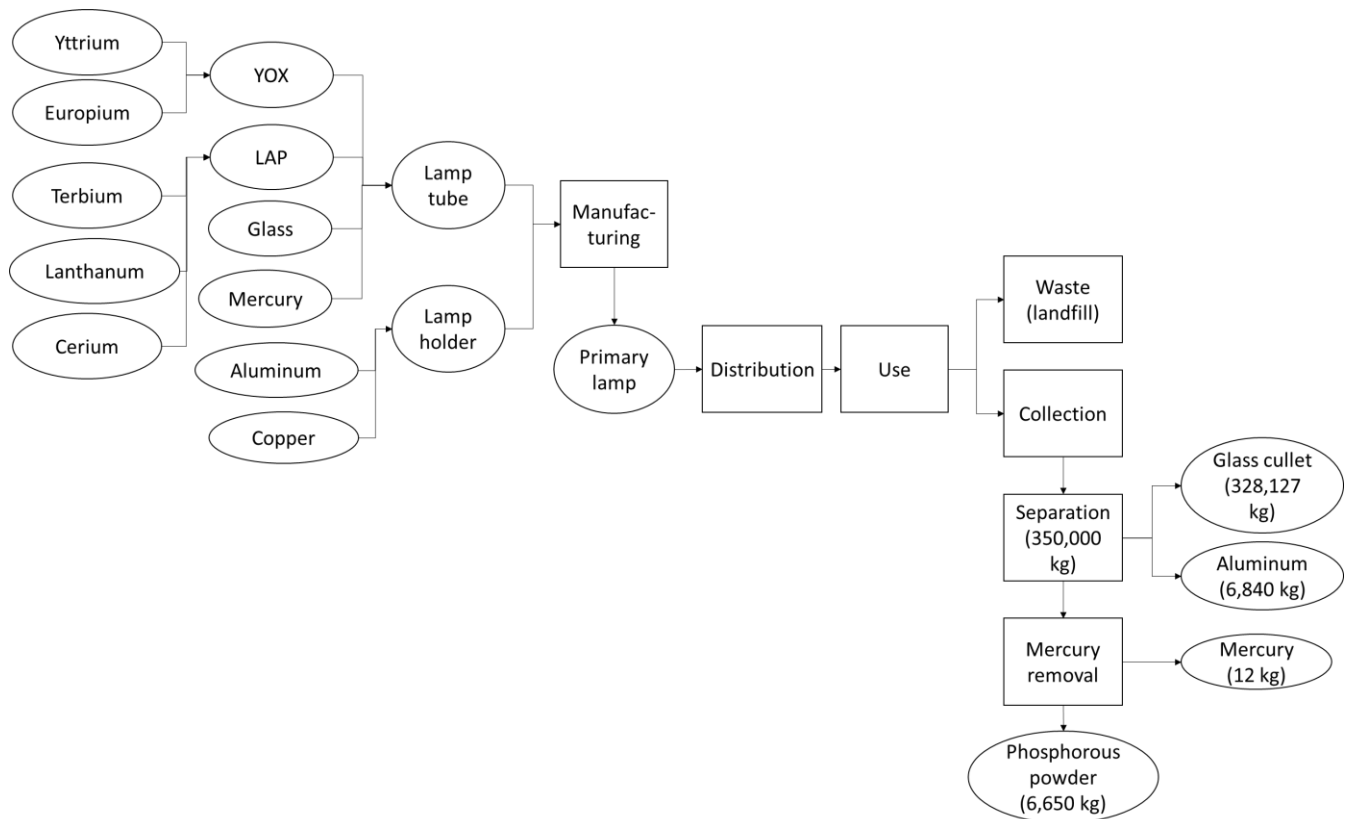


Figure 7B-7 Schematic overview of the life cycle of fluorescent lamps, based on the available data provided by Tan et al. (2015)

### 3.2.2.1. Primary production and waste treatment

As stated in Chapter 5, a recycled product is a co-product of the product system that provides the material for treatment. The material for treatment is at least the lamp tube, but the actual product that needs treatment at the end of life is the complete lamp, including the lamp holder. Part of the waste treatment process is shared between the lamp holder and the lamp tube. Also, if the lamp is not recycled, waste treatment of the complete lamp is needed. This makes the product system that provides the material for treatment the production process of the complete lamp. Therefore, the recycled glass and the recycled mix of REEs are accountable for the primary production of aluminum that is used for the lamp holder as well.

### 3.2.2.2. Distribution and the use phase

The lamps are packed and transported to their users, and electricity is used during the use phase of the lamp. It is obvious that the user of the lamp is responsible for the impacts related to these activities. The reduction of impacts during distribution and the use phase are also eco-design strategies similar to “design for recycling” (Maris et al 2014). These impacts can be influenced by the material choices that have been made in the production phase, for example, if the recyclable product is heavier than its single-use alternative. However, we consider that these activities should not be allocated between the lamp and the recycled materials because these impacts are user-specific. This is more easily illustrated if the lamp would not be recycled into separate materials but instead remanufactured and reused. Both the first and the second user of the lamp are responsible for impacts due to distribution and use, although these impacts can easily be influenced by the user himself. If the second user of the lamp uses solar energy to power the lamp, he should not be held responsible for fossil energy that was used in the first life cycle of the lamp.

### 3.2.3. Rearranging the system boundaries

The system boundaries are rearranged such that co-products are outputs of the product systems that provide the intermediate flows. Partitioning can now be applied on two levels: first, to identify the inventory that is attributed to the mix of REEs (Figure 7B-9). Then, this inventory and the inventory of the separation process are partitioned between the separated REEs (Figure 7B-10). As allocation already takes place between the individual REEs, the process to create recycled YOX is not a multifunctional process anymore (Figure 7B-8). Recycled YOX will be responsible for the impacts of “Process YOX” as well as the cradle-to-gate impacts of the intermediate flows, among which recycled yttrium and recycled europium.

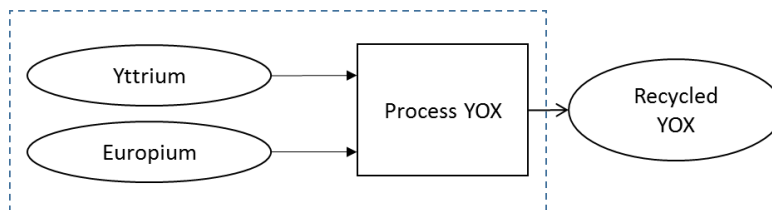


Figure 7B-8 Cradle-to-gate system boundaries of the simplified product system of recycled YOX where recycled yttrium and europium are one of the ingoing intermediate flows

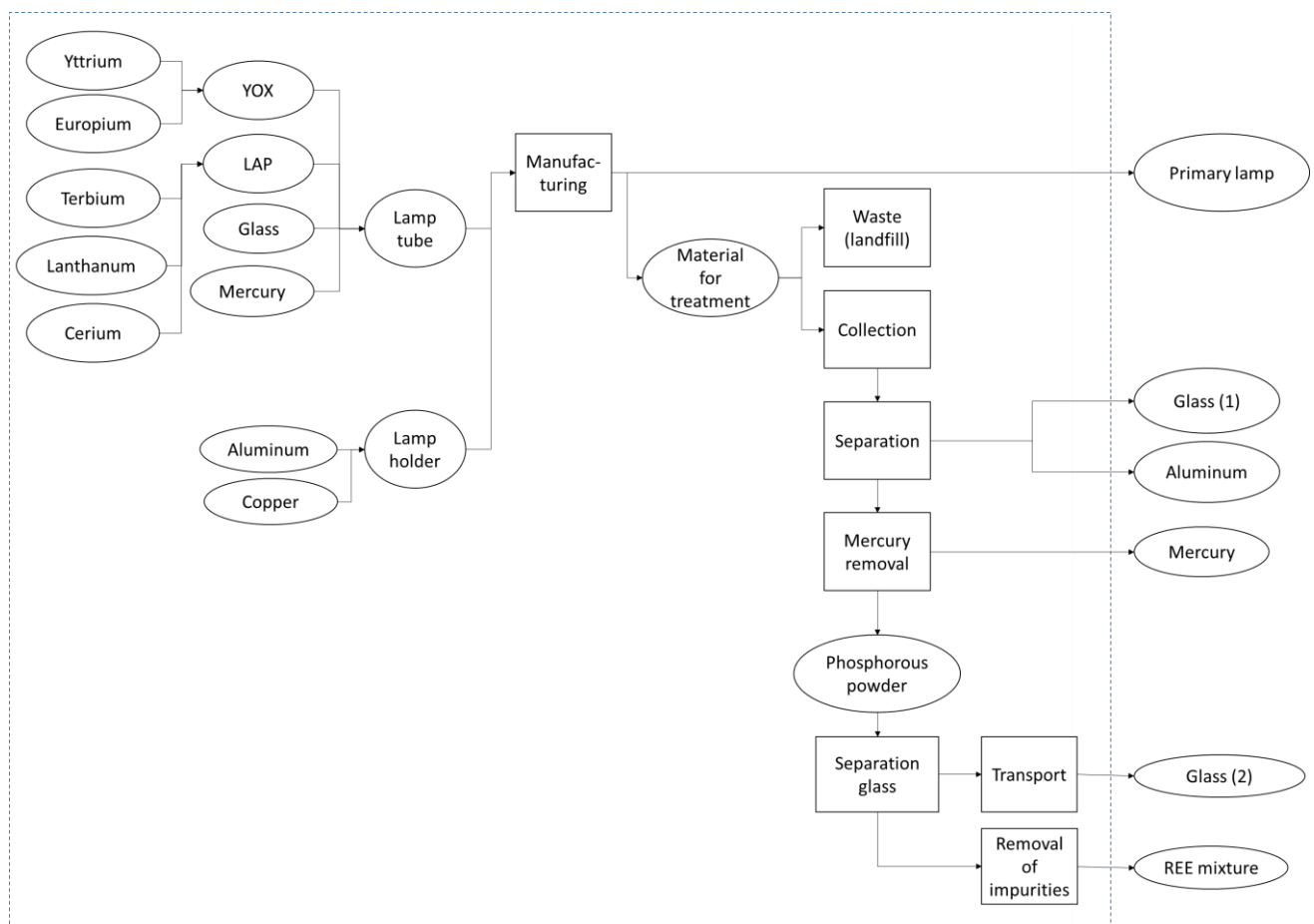


Figure 7B-9 Cradle-to-cradle system boundaries of the simplified product system of the fluorescent lamp and its co-products

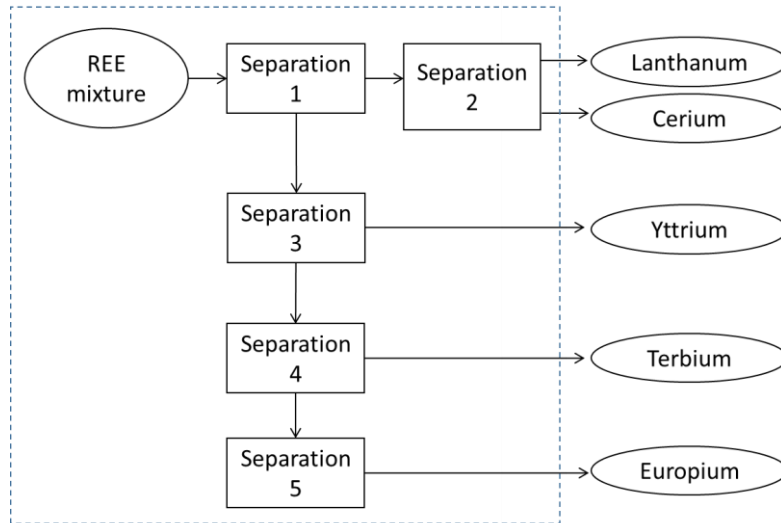


Figure 7B-10 Cradle-to-gate system boundaries of the simplified product system of the separated REEs

### 3.2.4. Applying “allocation at the point of substitution”

In Chapter 5, several formulas were presented that represent the APOS method. Here, only the formula for a product-oriented system is copied (Equation E9 of Chapter 5). However, the other equations of Chapter 5 are applicable as well.

$$E1. \quad E_{tot} = \left[ \sum_{i=1}^n CR_i * E_{tot(n-1)_i} * F_{(n-1)_i} + RI * E_d - RI * RRE * (E_d - E_r) + \sum_{i=1}^n (PR_i * E_{PR_i}) \right] * \frac{1}{(1 + \sum_{i=1}^n (PR_i * F_i))}$$

Table 7B-5 Legend of terms for Equation E1

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the first determining co-product	LCI/unit of analysis
$i$	Refers to an intermediate flow, recycled material or co-product that is used or produced in the life cycle of the first determining co-product	
CR	Consumption rate of an intermediate flow per unit of the product under study	Rate $\geq 0$
$E_{tot(n-1)}$	LCI attributed to the first determining co-product of the product system that supplies the intermediate flow	LCI/unit of analysis
RI	Production rate of a material at the end of life	Rate $\geq 0$
RRE	(End-of-life) recycling rate: share of the material at the end of life that is valorized	$0 \leq \dots \leq 1$
$E_d$	LCI due to waste treatment of the fraction of the material at the end of life that is not valorized	LCI/unit of analysis
$E_r$	LCI due to the valorization process of the material at the end of life, up to the production of a co-product	LCI/unit of waste
PR	Production rate of a co-product per unit of the product under study	Rate $\geq 0$
$E_{PR}$	LCI due to the valorization process related to the produced material (including LCI of material losses during the recycling process), per unit of the determining co-product of the valorization process	LCI / unit of valorized product

Term	Explanation	Value
F	Relative economic value between the recycled or recovered material or co-product and the first determining co-product (e.g. (€/MJ of electricity) / (€/kg of primary plastic))	Rate $\geq$ 0
F <sub>n-1</sub>	Relative economic value between the recycled/recovered material or co-product and the first determining co-product that were produced in the product system that supplies the intermediate flow	Rate $\geq$ 0

#### 3.2.4.1. Identify the impacts of the REE mix

Considering that the impacts up to manufacturing and the impacts of the end of life stage of the lamps should be shared between all co-products, allocation at the point of substitution can be applied. The allocation factors are calculated in Table 7B-6. As the REE mix is not traded in this form, it is difficult to identify the market price of this product. Following the ILCD Handbook, the market price can be derived by “[...] combining production cost information and the market price of the further processed, packed, transported etc. co-product. Any additional steps of transport, conditioning, packaging etc. are to be considered to make sure the economic value used for allocation actually reflects the value of each co-product at the point and in the condition where it is delivered.” (European Commission 2010). From the primary production route, it appeared that the REO ore with an REO content of 61% might have a market value of 3% of the final separated REOs. It is assumed here that the price of the REE mix just before separation is 60% of the value of the separated elements. This percentage is varied between 10-90% in an uncertainty analysis. Inventory data have been published by Tan et al. (2015) for the manufacturing and the disposal of the lamp. As some intermediate flows from this publication are not available in ecoinvent, datasets have been chosen that correspond most to the description in the publication. The inventory related to the recycled aluminum, mercury and glass cullet are adjusted to the inventory of the linear lamp, to avoid recycling rates higher than 100%.

Table 7B-6 Allocation factors of the co-products produced by the product system of the fluorescent lamp

Data source	Co-products	Quantity		Unit price		Revenue	Allocation factor
(Tan et al 2015)	Fluorescent lamps	3.4E+06	p	1.72 <sup>a</sup>	USD/p	\$5,779,117	96.84%
	Glass cullet	3.3E+05	kg	0.34 <sup>a</sup>	USD/kg	\$111,563	1.87%
	Aluminum	6.8E+03	kg	1.50 <sup>a</sup>	USD/kg	\$10,260	0.17%
	Mercury	1.2E+01	kg	60.00 <sup>a</sup>	USD/kg	\$720	0.01%
	Phosphorous powder	6.7E+03	kg				
(Lartigue-Peyrou 2016)	Glass cullet	1.4E+03	kg	0.34 <sup>a</sup>	USD/kg	\$467	0.01%
	REE mix	9.3E+02	kg	70.13 <sup>b</sup>	USD/kg	\$65,459	1.10%
					Total revenue	\$5,971,899	100.00%

<sup>a</sup>Prices based on average in France and EU28 from the years 2010-2015 (data.un.org)

<sup>b</sup>Assumption that the REE mix has a price of 60% of the value of the separated elements. This is varied between 10-90% in an uncertainty analysis

#### Mathematical approach to calculating the impacts of the REE mix

Equation E1 is applied to calculate first the inventory of the primary lamp – i.e. the “first determining co-product” of the equation. The values for the parameters of Equation E2 are given in Table 7B-7. The parameters are graphically represented in Figure 7B-11.

$$E2. \quad E_{tot\ lamp} = \left[ \sum_{i=1}^n CR_i * E_{tot(n-1)_i} * F_{(n-1)_i} + RI * E_d - RI * RRE * (E_d - E_r) + \sum_{i=1}^n (PR_i * E_{PR_i}) \right] * \frac{1}{(1 + \sum_{i=1}^n (PR_i * F_i))}$$

From the inventory of the lamp, the inventory of the REE mix can be calculated as follows:

$$E3. \quad E_{tot\ REE} = E_{tot\ lamp} * F_{REE}$$

Table 7B-7 Values of the parameters of Equation E2

	Cradle-to-gate lamp	End-of-life lamp	Glass (1)	Aluminum	Mercury	Glass (2)	REE mixture
CR	1 p						
$E_{tot(n-1)}$	$E_{vlamp}$						
$F_{(n-1)}$	1						
RI		1 p					
$E_d$		$E_{dlamp}$					
RRE		1					
$E_r$		$E_{rlamp}$					
PR			$\frac{3.3E+05}{3.4E+06}$	$\frac{6.8E+03}{3.4E+06}$	$\frac{1.2E+01}{3.4E+06}$	$\frac{1.4E+03}{3.4E+06}$	$\frac{9.3E+02}{3.4E+06}$
$E_{PR}$			0	0	$E_{PRmerc}$	$E_{PRglass}$	$E_{PRREE}$
F			$\frac{0.34}{1.72}$	$\frac{1.50}{1.72}$	$\frac{60.00}{1.72}$	$\frac{0.34}{1.72}$	$\frac{70.13}{1.72}$

#### 3.2.4.2. Identify the impacts of the recycled REEs

The inventory that is attributed to the REE mix, as well as the inventory of the separation process, is partitioned between the individual rare earth elements according to Table 7B-8.

Table 7B-8 Allocation factors of the co-products of the separation of the REE mixture

Output of separation of 1 kg of REE mix	Mass (kg)	Market price 2013 (USD/kg) <sup>a</sup>	Revenue (USD)	Allocation factor
Lanthanum	1.3E-01	7.866	\$1	0.87%
Cerium	1.0E-01	7.863	\$1	0.68%
Yttrium	6.7E-01	26	\$17	14.92%
Terbium	4.7E-02	920	\$43	37.19%
Europium	4.9E-02	1095	\$54	46.33%
		Total	\$117	100%

<sup>a</sup>(Statista 2016a)

#### Mathematical approach to calculating the impacts of the individual REEs

Again, Equation E1 is used to calculate the inventory of each REE. Equation E4 calculates the inventory attributed to the recycled europium. This parameter *RI* refers in this equation to a product at the end of life. We are calculating the inventory from cradle-to-gate, which is why this term is irrelevant. In



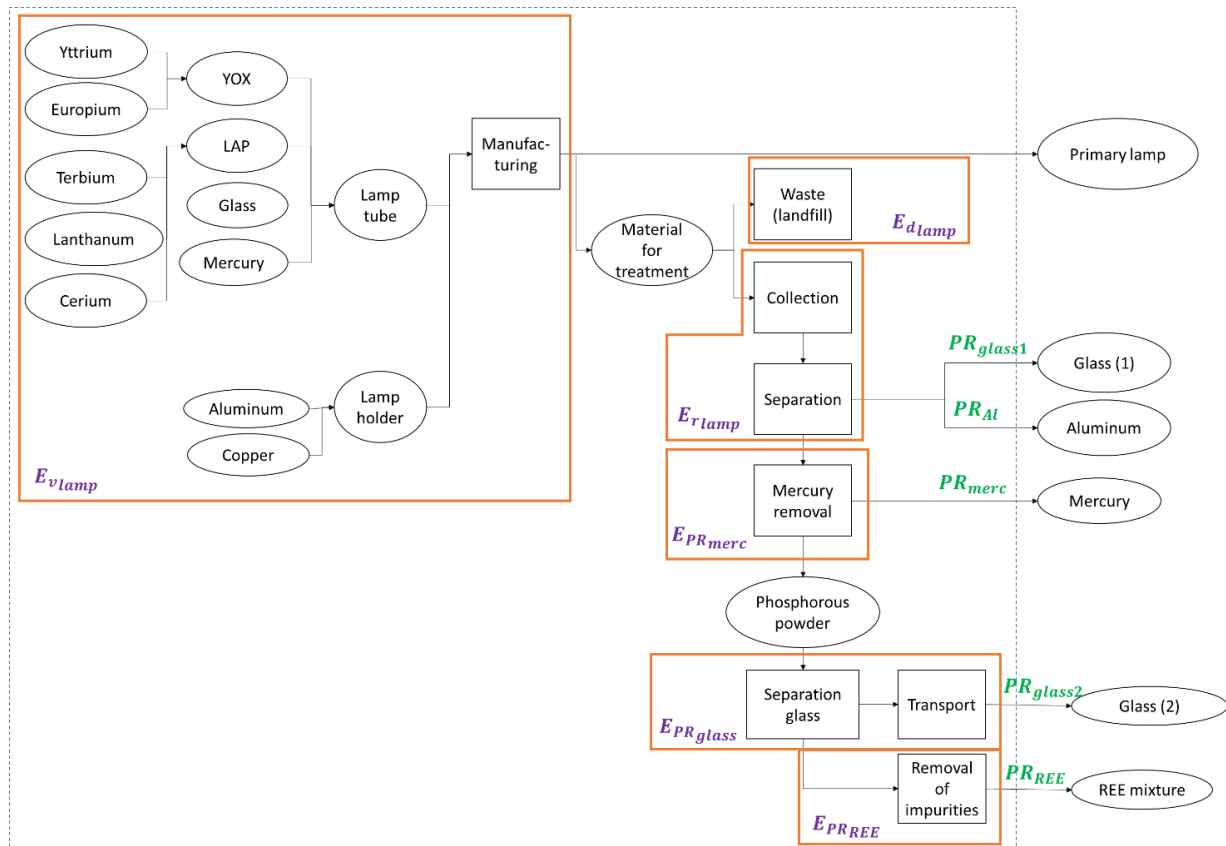


Figure 7B-11 Graphical representation of the parameters of Table 7B-7

principle, each REE could be used as a reference. This influences the calculation of  $PR$  and  $F$ , which are in the current calculation relative to the production and the price of europium. The values of the parameters of Equation E4 are given in Table 7B-9 and the terms are graphically represented in Figure 7B-12.

$$E4. \quad E_{totEu} = \left[ \sum_{i=1}^n CR_i * E_{tot(n-1)_i} * F_{(n-1)_i} + RI * E_d - RI * RRE * (E_d - E_r) + \sum_{i=1}^n (PR_i * E_{PRi}) \right] * \frac{1}{(1 + \sum_{i=1}^n (PR_i * F_i))}$$

Table 7B-9 Values of the parameters of Equation E4

	REE mixture	Other intermediate inputs	Lanthanum	Cerium	Yttrium	Terbium
CR	CR <sub>REE</sub>	CR <sub>other</sub>				
E <sub>tot(n-1)</sub>	E <sub>totlamp</sub>	E <sub>vother</sub>				
F <sub>(n-1)</sub>	F <sub>REE</sub>	1				
PR			$\frac{1.3E-01}{4.9E-02}$	$\frac{1.0E-01}{4.9E-02}$	$\frac{6.7E-01}{4.9E-02}$	$\frac{4.7E-02}{4.9E-02}$
E <sub>PR</sub>			0	E <sub>PRCe</sub>	0	0
F			$\frac{7.866}{1095}$	$\frac{7.863}{1095}$	$\frac{26}{1095}$	$\frac{920}{1095}$

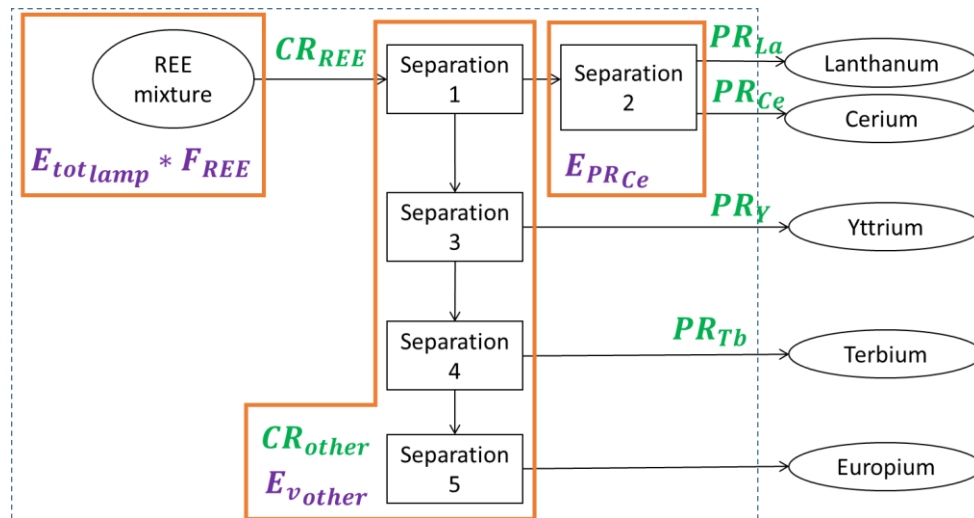


Figure 7B-12 Graphical representation of the parameters of Table 7B-9

#### 3.2.4.3. Mathematical approach to calculating the impacts of recycled YOX

Finally, the inventory of YOX can be calculated by Equation E5. Only the cradle-to-gate inventory is calculated and no co-products are produced during this process, which simplifies the equation. The parameters are represented by the values of Table 7B-10 and Figure 7B-13.

$$E5. \quad E_{totYOX} = \left[ \sum_{i=1}^n CR_i * E_{tot(n-1)_i} * F_{(n-1)_i} + RI * E_d - RI * RRE * (E_d - E_r) + \sum_{i=1}^n (PR_i * E_{PR_i}) \right] * \frac{1}{(1 + \sum_{i=1}^n (PR_i * F_i))}$$

Table 7B-10 Values of the parameters of Equation E5

	Yttrium	Europium	Other intermediate inputs
CR	CR <sub>Y</sub>	CR <sub>Eu</sub>	CR <sub>other</sub>
E <sub>tot(n-1)</sub>	E <sub>totEu</sub>	E <sub>totEu</sub>	E <sub>vother</sub>
F <sub>(n-1)</sub>	F <sub>Yttrium</sub>	1	1

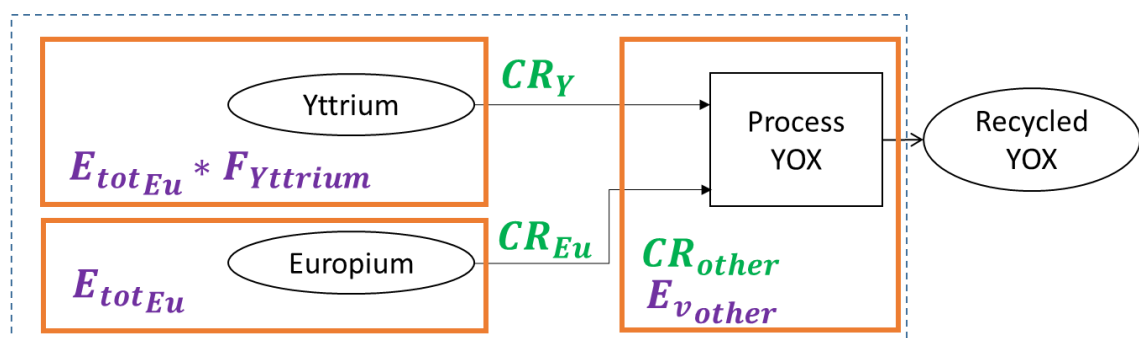


Figure 7B-13 Graphical representation of the parameters of Table 7B-10

## 4. Impact assessment and interpretation

In this chapter, several different LCA goals with different functional units have been analyzed. The analyses give different results which require each a slightly different interpretation. The results

respond to the LCA goal under study, and cannot always be used to answer a different goal. In this section, we show how the results can be interpreted and where the results can be used for.

#### 4.1. Process-oriented LCA

This section shows the results of the process-oriented LCAs. The results are given for the different purposes and functional units, as described in the goal and scope definition.

##### 4.1.1. Quantifying environmental impacts

*For what environmental impacts are the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps accountable?*

According to Table 7B-11, the production process of recycled YOX is accountable for 6E+01 kg CO<sub>2</sub>-eq, which contributes to Climate Change. This result could be used for the environmental labeling of a production route. If a company that recycles REEs would conduct a hotspot analysis of the complete organization, this result would represent the recycling process for YOX.

Table 7B-11 Environmental impacts attributed to production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps

Impact category	Unit	Total
Climate change	kg CO <sub>2</sub> eq	6E+01
Ozone depletion	kg CFC-11 eq	1E-05
Human toxicity, non-cancer effects	CTUh	1E-05
Human toxicity, cancer effects	CTUh	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	4E-02
Ionizing radiation HH	kBq U235 eq	3E+01
Ionizing radiation E (interim)	CTUe	6E-05
Photochemical ozone formation	kg NMVOC eq	1E-01
Acidification	molc H <sup>+</sup> eq	3E-01
Terrestrial eutrophication	molc N eq	4E-01
Freshwater eutrophication	kg P eq	8E-03
Marine eutrophication	kg N eq	4E-02
Freshwater ecotoxicity	CTUe	4E+02
Land use	kg C deficit	8E+01
Water resource depletion	m <sup>3</sup> water eq	2E-01
Mineral, fossil & ren resource depletion	kg Sb eq	2E-03

##### 4.1.2. Identification of options for improvement

*How can we reduce the environmental impacts of the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps, in order to reduce its accountability for impacts?*

As Figure 7B-14 shows, the treatment of the phosphorous powder is the largest contributor to the impacts of the recycling process. If impacts are to be reduced, lowering the impacts of this step in the recycling process might lead to the highest impact reductions.

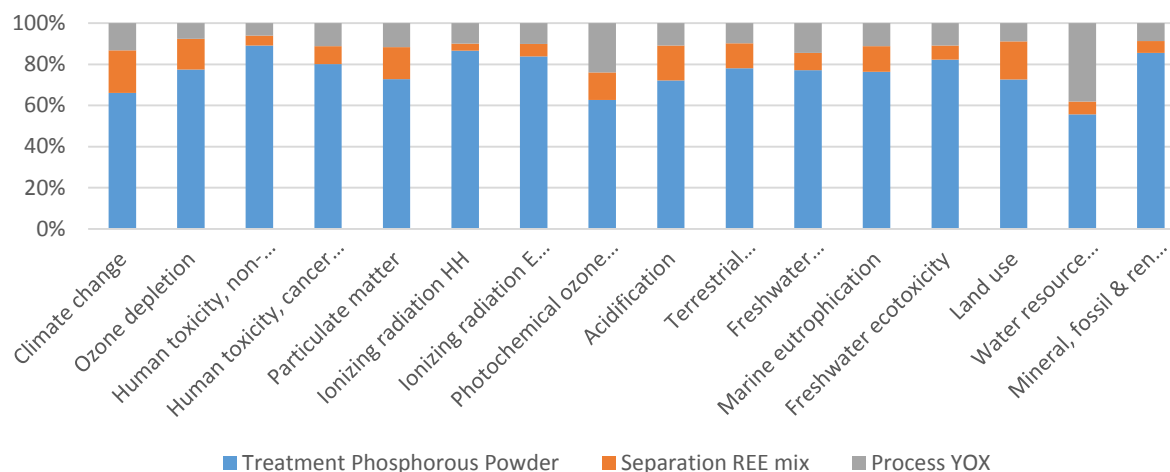


Figure 7B-14 Contribution analysis of the recycling process of 1 kg of recycled YOX

#### 4.1.3. Decision-making

In this section, we investigated two different purposes: benchmarking and environmental profile management. For these applications, different research questions were asked.

##### Benchmarking

*Is the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps less accountable for environmental impacts than alternative production and treatment processes of these products?*

The recycling route is accountable for lower impacts than the alternative route using average processes (Figure 7B-15). However, the recycling route is accountable for higher impacts related to ionizing radiation. This is due to the fact that the French electricity mix is dominated by nuclear energy. The recycling route is responsible for lower environmental impacts related to Climate Change, due to the fact that the primary production of YOX and terbium oxide – which is produced as a co-product in the recycling process – are accountable for high impacts (Figure 7B-16).

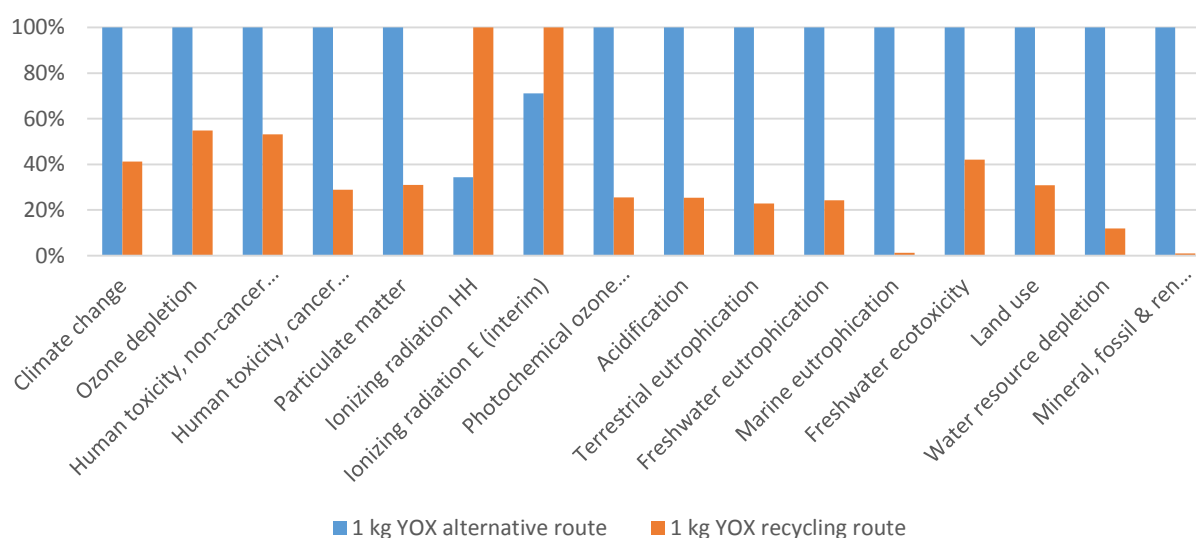


Figure 7B-15 Comparison of the impacts attributed to the recycling route and an alternative production route for 1 kg of YOX. The functional units are the same. The results are represented relative to the alternative with the highest impacts, which is set to 100%

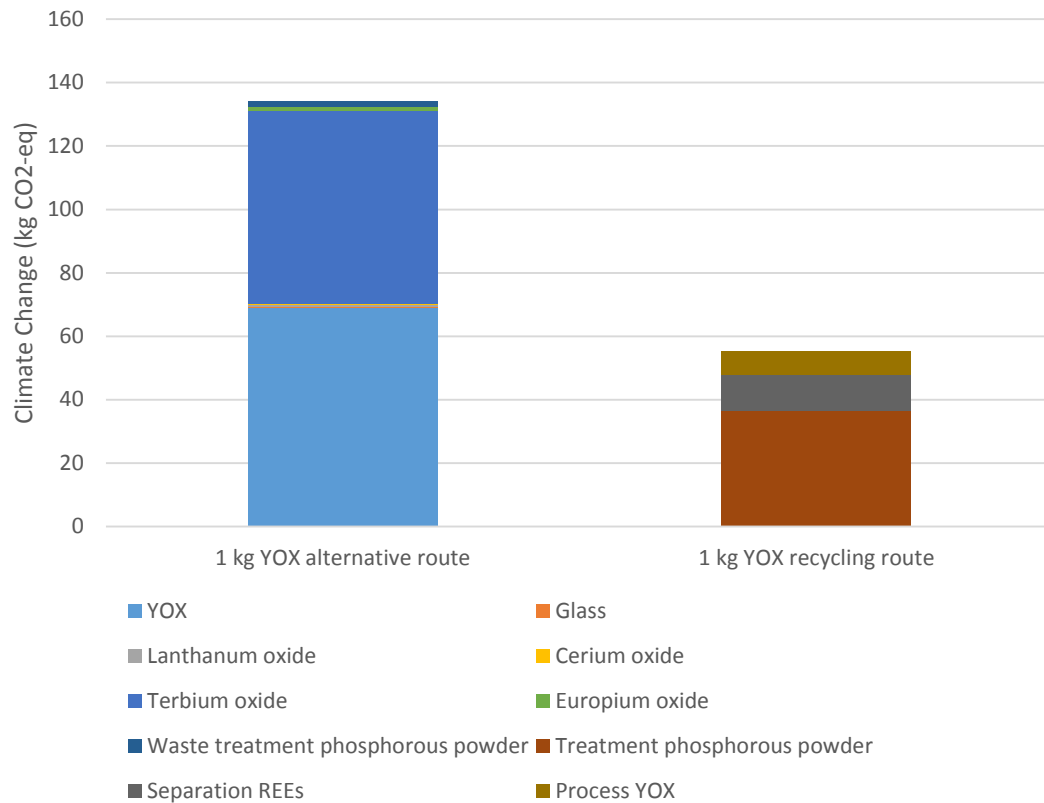


Figure 7B-16 Comparison of the impacts related to Climate Change attributed to the recycling route and an alternative production route for 1 kg of YOX. The functional units are the same

#### Environmental portfolio management

*Is a company accountable for lower impacts due to the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps than due to the production of primary REEs?*

Similar results are obtained with the functional unit that excludes the waste treatment of phosphorous powder and the primary production of glass (Figure 7B-17). Therefore, if the REE producer decides to produce less YOX and other REEs via the primary production route, and more via the recycling route, this company becomes less responsible for environmental impacts. This could enable the decision to change the company's production portfolio, for example, to meet carbon emission targets. In this comparison, it is not important whether different production routes provide the same functions, but only which functions that are provided by the stakeholder could be displaced. Therefore, instead of using average data in the alternative route, actual data on the processes that are avoided within the company have the preference.

In this assessment, the results for benchmarking and environmental portfolio management in the process-oriented LCA are very similar. However, this does not always have to be the case. In this example, the REE producer produces both primary and recycled REEs. Because the impacts of primary REEs are large contributors to the impacts of the alternative production route, the stakeholder could reduce the company's impact profile by producing more recycled REEs. However, if the company under study were a glass company that recycles the phosphorous powder to obtain recycled glass and recycled REEs, the conclusion would be different. Although benchmarking would still show the relatively low impact of the recycling route, the environmental profile of the company would be more

impactful. This is due to the fact that the treatment of the phosphorous powder is responsible for higher impacts than the primary production of glass. This type of analysis could indicate which actor would profit most from the in-house implementation of the recycling route, from an environmental perspective.

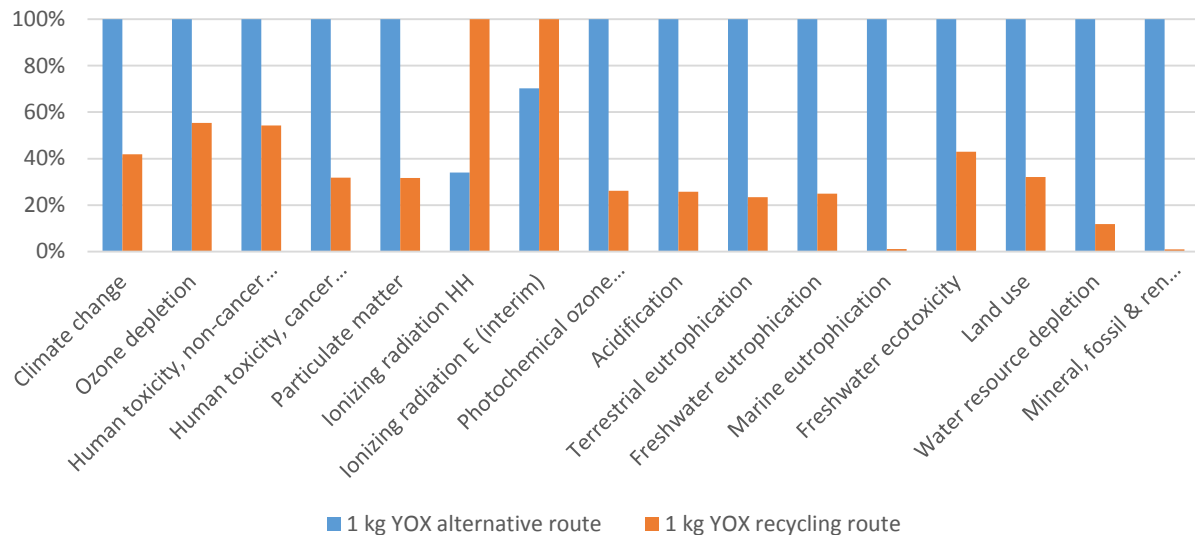


Figure 7B-17 Comparison of the impacts attributed to the recycling route and an alternative production route for 1 kg of YOX. The functional units are not the same: the alternative route only includes functions that were already provided by the REE producer. The results are represented relative to the alternative with the highest impacts, which is set to 100%

## 4.2. Product-oriented LCA on 1 kg of recycled YOX

In this section, the results are presented of the product-oriented LCAs. The results are given for the different purposes and functional units, as described in the goal and scope definition and in Section 2.

### 4.2.1. Quantifying impacts

*For what environmental impacts is the demand for 1 kg of recycled YOX accountable?*

The demand for 1 kg of recycled YOX is accountable for 3E+01 kg CO<sub>2</sub>-eq (Table 7B-12). Note that this result is different than the result of the production process of recycled YOX, due to the fact that allocation is applied between the co-products of the recycling process, and between the fluorescent lamp and the REE mix. This result can be used in an LCA study that uses recycled YOX as a material input.

### 4.2.2. Identification of options for improvement

*How can we decrease the impact of the demand for 1 kg of recycled YOX, in order to reduce its accountability for impacts?*

Figure 7B-18 shows that the largest contributor to the impacts of recycled YOX is the consumption of recycled europium and recycled yttrium. Although a much smaller quantity of europium than yttrium is used, the allocation factor of europium is much higher than the one for yttrium due to the high market price for europium in 2013. The impacts attributed to recycled europium are mainly due to the impacts of the REE mix from the product system of the fluorescent lamp (Figure 7B-19). The impacts for which the REE mix is accountable are mainly caused by the lamp tube and to a smaller extent the lamp holder (Figure 7B-20). The treatment process of the phosphorous powder has a small contribution to the total impacts, with the exception of ionizing radiation.

Table 7B-12 Environmental impacts attributed to 1 kg of recycled YOX

Impact category	Unit	Total
Climate change	kg CO2 eq	3E+01
Ozone depletion	kg CFC-11 eq	4E-06
Human toxicity, non-cancer effects	CTUh	2E-05
Human toxicity, cancer effects	CTUh	2E-06
Particulate matter	kg PM2.5 eq	3E-02
Ionizing radiation HH	kBq U235 eq	5
Ionizing radiation E (interim)	CTUe	1E-05
Photochemical ozone formation	kg NMVOC eq	1E-01
Acidification	molc H+ eq	2E-01
Terrestrial eutrophication	molc N eq	3E-01
Freshwater eutrophication	kg P eq	9E-03
Marine eutrophication	kg N eq	2E-01
Freshwater ecotoxicity	CTUe	3E+02
Land use	kg C deficit	7E+01
Water resource depletion	m3 water eq	2E-01
Mineral, fossil & ren resource depletion	kg Sb eq	2E-02

In contrast to the hotspot identification of the production process of recycled YOX, main contributors to the impact of the demand for recycled YOX are processes that are difficult to influence by the user of recycled YOX. However, to reduce his accountability for impacts, this user can decide to use recycled YOX from a different production route than the recycling route of phosphorous powder from fluorescent lamps.

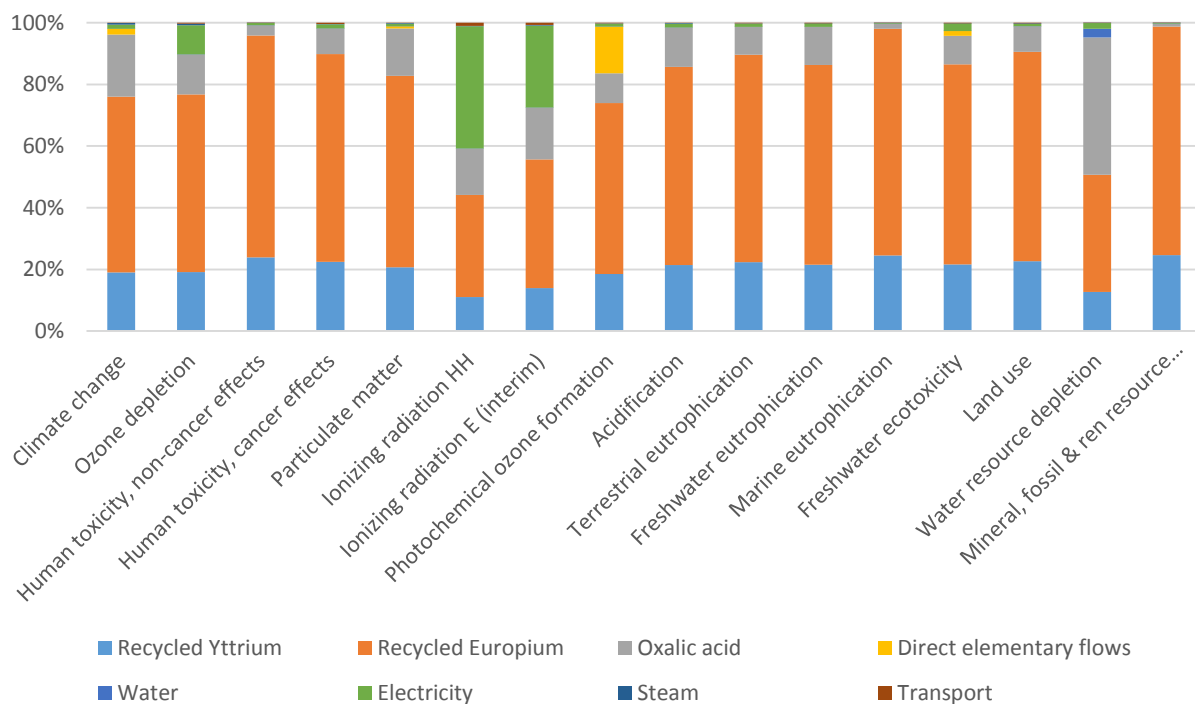


Figure 7B-18 Contribution analysis of the demand for 1 kg of recycled YOX

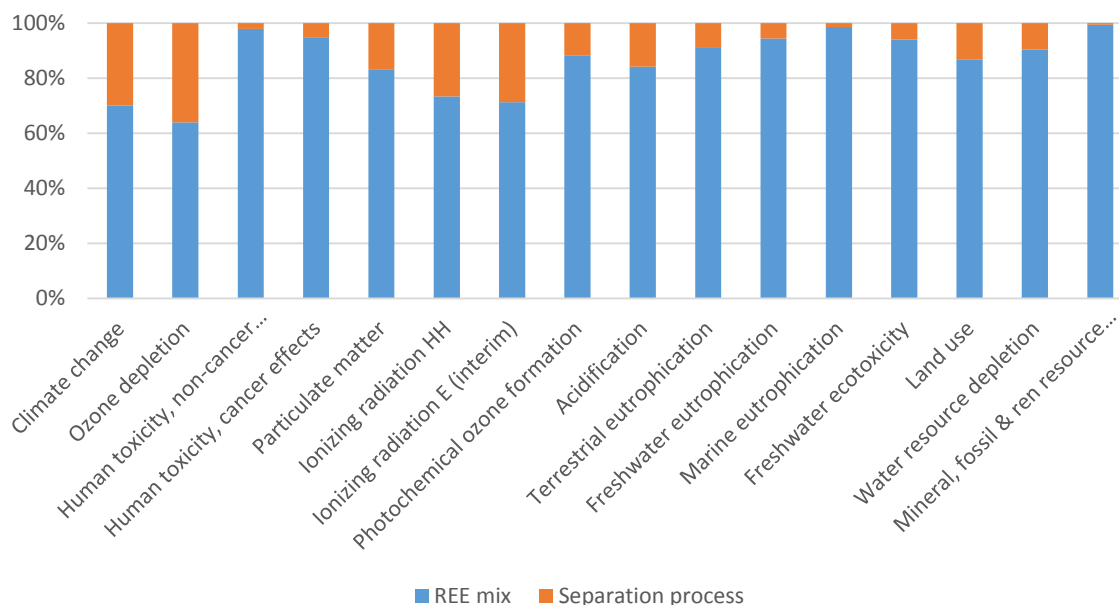


Figure 7B-19 Contribution analysis of the demand for 1 kg of recycled Europium

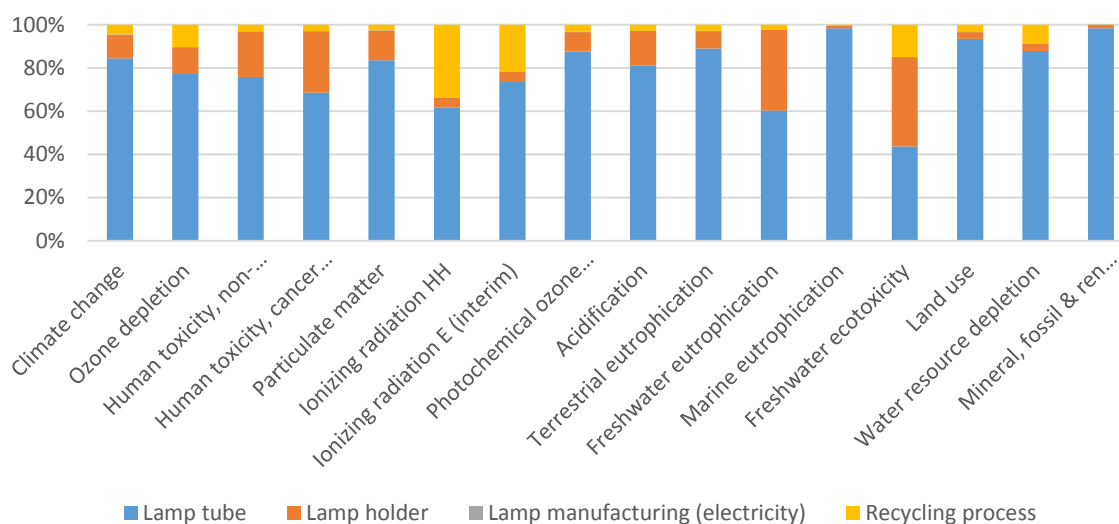


Figure 7B-20 Contribution analysis of the demand for 1 kg of REE mix

#### 4.2.3. Decision-making

*Is the demand for 1 kg of recycled YOX less accountable for impacts than the demand for 1 kg of primary YOX?*

For almost all impact categories, the demand for 1 kg of recycled YOX is accountable for lower impacts than the demand 1 kg of primary YOX (Figure 7B-21). The high impacts on human toxicity (non-cancer effects) is caused by the use of mercury in lamp tubes. The contribution analysis of climate change (Figure 7B-22) shows a similar pattern between the contribution of primary and recycled YOX, with regard to the contribution of impacts of yttrium and europium.



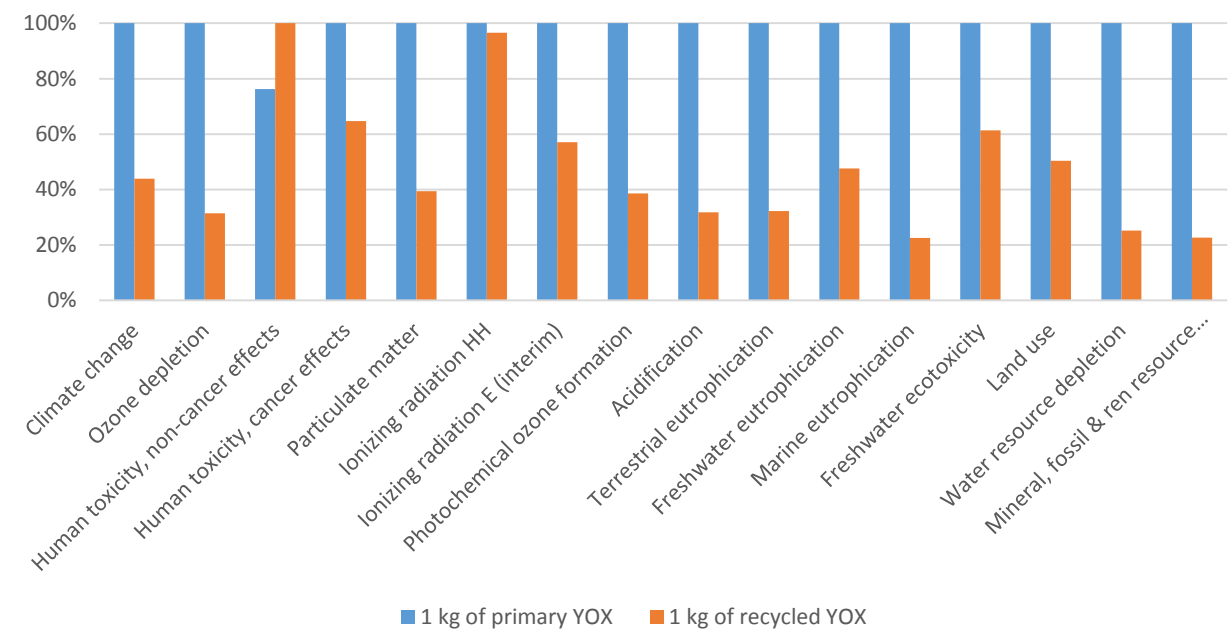


Figure 7B-21 Comparison of the impacts attributed to the demand for 1 kg of primary YOX and recycled YOX. The results are represented relative to the alternative with the highest impacts, which is set to 100%

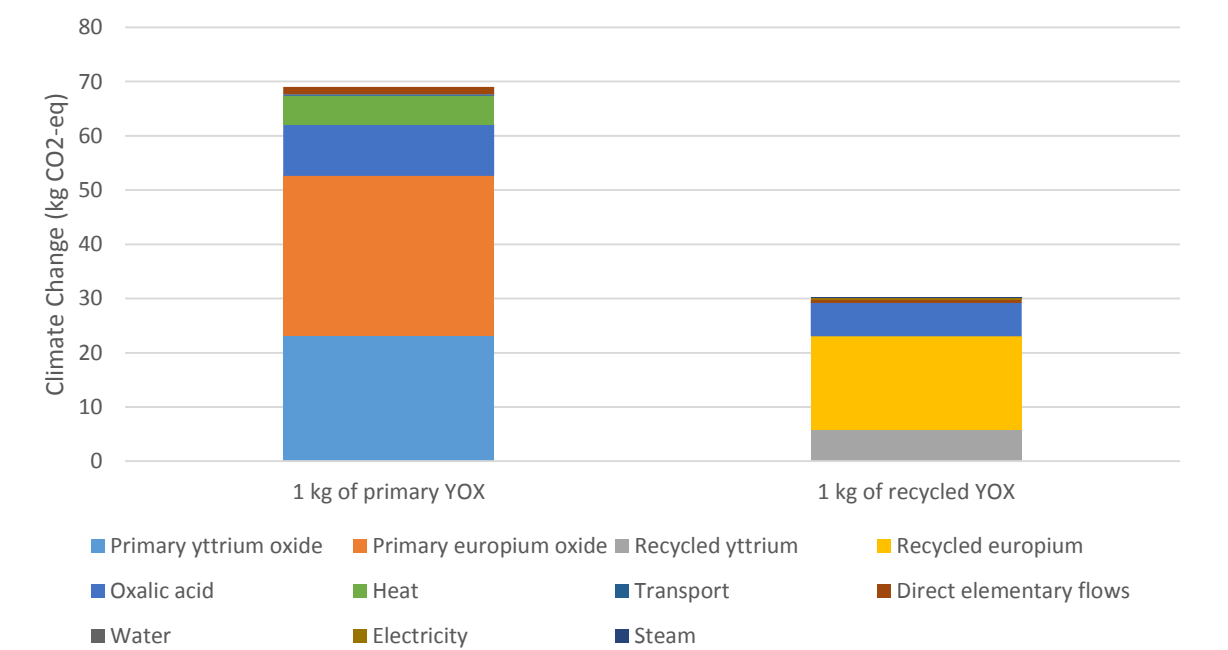


Figure 7B-22 Comparison of the impacts related to Climate Change attributed to the demand for 1 kg of primary and recycled YOX

### 4.3. Product-oriented LCA on 1 fluorescent lamp

#### 4.3.1. Quantifying impacts

*For what environmental impacts is the demand for 1 fluorescent lamp accountable?*

Table 7B-13 shows that 1 fluorescent lamp – of which only the phosphorous powder is not recycled – is accountable for the emission of 5E-01 kg CO<sub>2</sub>-equivalent, which contribute to Climate Change. It should be repeated that this only concerns impacts related to the manufacturing and disposal of a lamp. Impacts generated during distribution and the use phase are not included.

Table 7B-13 Environmental impacts attributed to the demand for 1 fluorescent lamp

Impact category	Unit	Total
Climate change	kg CO <sub>2</sub> eq	5E-01
Ozone depletion	kg CFC-11 eq	5E-08
Human toxicity, non-cancer effects	CTUh	6E-07
Human toxicity, cancer effects	CTUh	4E-08
Particulate matter	kg PM <sub>2.5</sub> eq	5E-04
Ionizing radiation HH	kBq U235 eq	5E-02
Ionizing radiation E (interim)	CTUe	2E-07
Photochemical ozone formation	kg NMVOC eq	2E-03
Acidification	molc H <sup>+</sup> eq	4E-03
Terrestrial eutrophication	molc N eq	8E-03
Freshwater eutrophication	kg P eq	2E-04
Marine eutrophication	kg N eq	6E-03
Freshwater ecotoxicity	CTUe	7
Land use	kg C deficit	2
Water resource depletion	m <sup>3</sup> water eq	2E-03
Mineral, fossil & ren resource depletion	kg Sb eq	5E-04

#### 4.3.2. Identification of options for improvement

*How can we decrease the impact of the demand for 1 fluorescent lamp, in order to reduce its accountability for impacts?*

It appears from Figure 7B-23 that the impacts of the lamp are mainly caused by the lamp tube and the lamp holder. The consumption of glass is the largest contributor to the impacts of the lamp tube (Figure 7B-24). Also the use of primary LAP and YOX are relevant contributors. The impacts of LAP are mainly caused by the use of terbium. The impacts on human toxicity (non-cancer effects) are dominated by the use of mercury in the lamp tube. In the lamp holder, impacts are mainly caused by the use of aluminum and copper (Figure 7B-25). The impacts of the lamp might be decreased if the lamp would use recycled instead of primary materials.

Primary aluminum and glass have a beneficial effect on water resource depletion, due to the fact that in these datasets the water outflows are assessed with a negative characterization factor, which is higher than the characterization factor of the water inflows. This is, however, a result of an incompatibility between the inventory within the ecoinvent database and the ILCD impact assessment method.

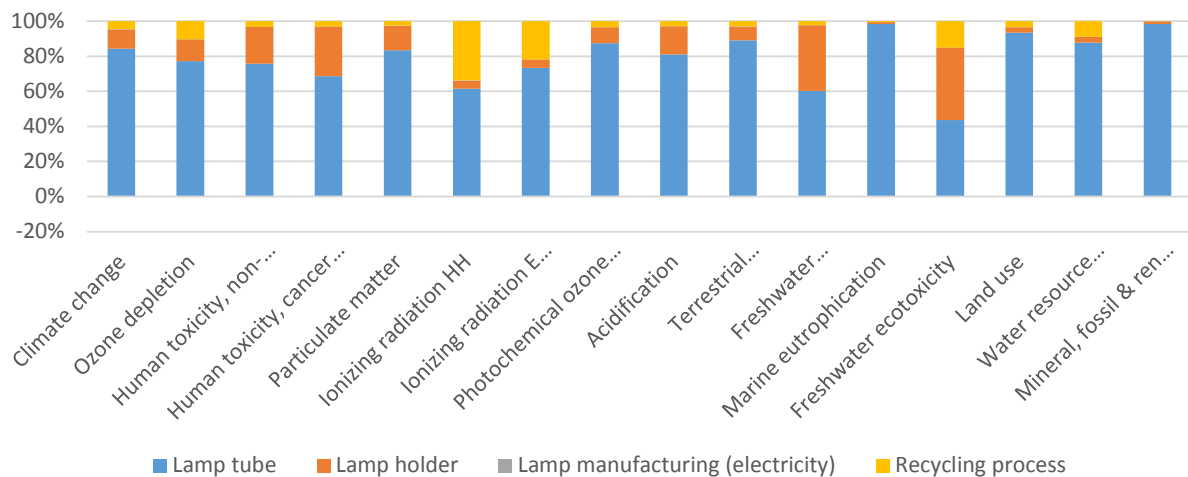


Figure 7B-23 Contribution analysis of the demand for 1 fluorescent lamp

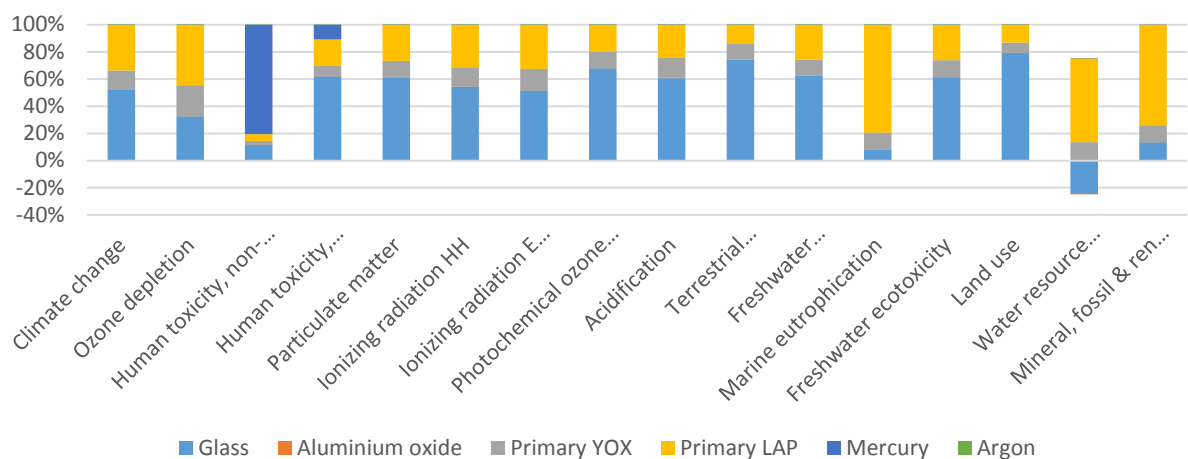


Figure 7B-24 Contribution analysis of the demand for 1 p of lamp tube

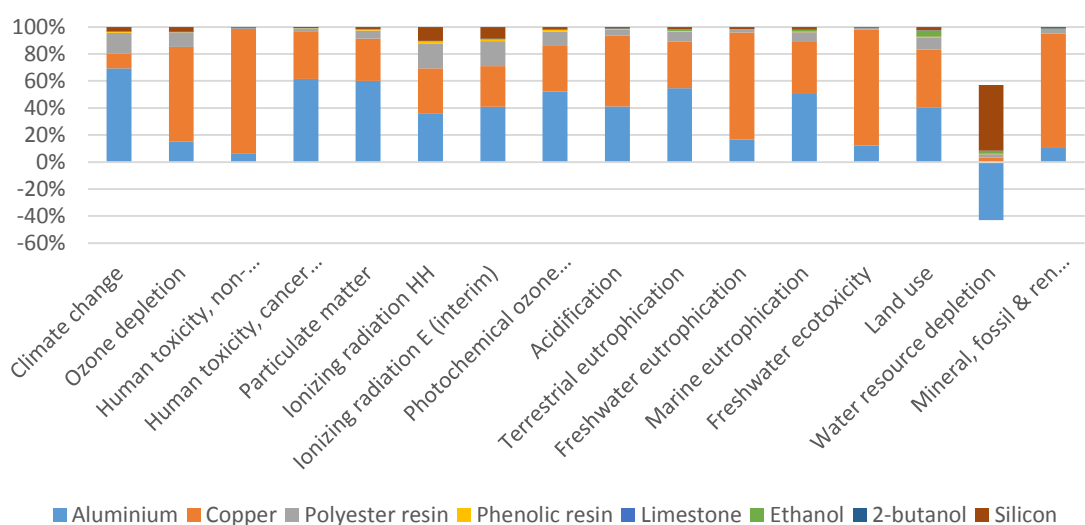


Figure 7B-25 Contribution analysis of the demand for 1 p of lamp holder

#### 4.3.3. Decision-making

Which of the following lamps is accountable for lower impacts?

- 1 fluorescent lamp that is not involved with the valorization process
- 1 fluorescent lamp that only valorizes the phosphorous powder at the end of life, or
- 1 fluorescent lamp that contains recycled YOX and valorizes the phosphorous powder at the end of life

The results of this analysis are presented in Figure 7B-26. For the lamp that uses recycled YOX, it is assumed that the recycled content is equal to the end-of-life recycling rate, i.e. 24%. The results show that recycling of the phosphorous powder at the end of life slightly increases the impacts for which the lamp is accountable (pay attention to the scale of the y-axis). The use of recycled YOX decreases the accountability for impacts marginally for some impact categories.

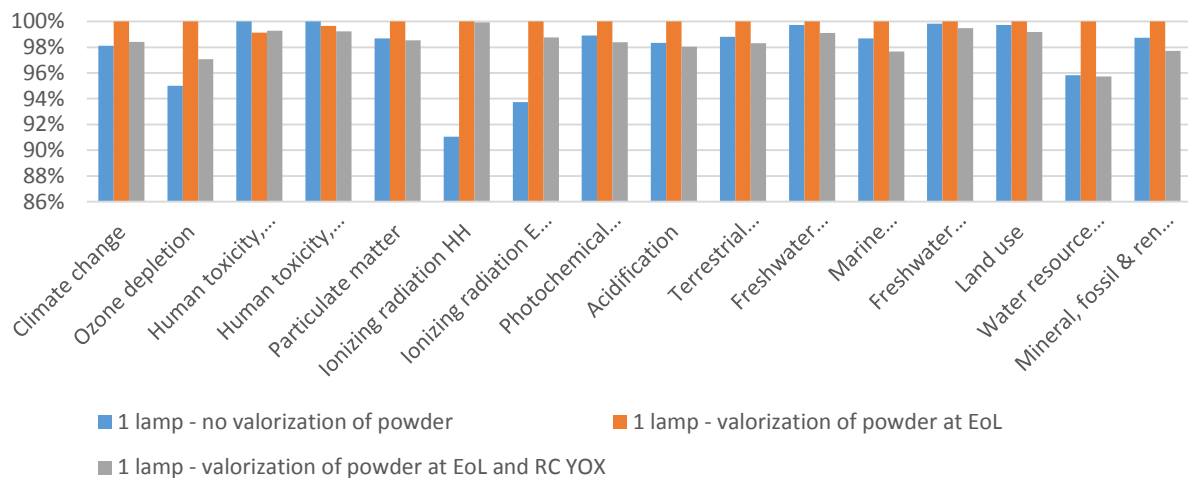


Figure 7B-26 Comparison of the impacts attributed to the demand for 1 fluorescent lamp with a varying degree of involvement in recycling activities. The results are represented relative to the alternative with the highest impacts, which is set to 100%

However, not only YOX is recycled. Even when the phosphorous powder is not valorized, aluminum, mercury, and glass (referred to as “glass (1)”) are already recycled. The lamp might be able to use these materials in a closed loop as well. Furthermore, besides recycled YOX, other materials are recycled from the powder as well. These are the additionally recycled glass (i.e. “glass (2)”), the recycled cerium, lanthanum and terbium and the excess of europium that is not used in YOX. Therefore, the following lamps are compared as well, to identify the relevance of using each of the recycled materials as recycled content:

1. 1 lamp that valorizes the powder at the end of life
2. 1 lamp that valorizes the powder at the end of life and uses recycled aluminum, mercury and glass (1) in a closed loop
3. 1 lamp that valorizes the powder at the end of life and uses recycled aluminum, mercury, glass (1) and YOX in a closed loop
4. 1 lamp that valorizes the powder at the end of life and uses recycled aluminum, mercury, glass (1 and 2), YOX and the other recycled REEs in a closed loop

In the lamp that contains recycled materials, it is assumed that the same quantity of recycled materials is used as the amount that is produced at the end of life. This means that all materials are used as if it were a closed loop. This assumption is also done for the use of recycled glass cullet, although it was

stated before that the recycled glass can probably not directly replace primary glass. However, this uncertainty is considered irrelevant in this comparison.

Figure 7B-27 shows that the impacts attributed to a lamp can be highly decreased by the consumption of recycled aluminum, mercury, and glass, with the exception of water resource depletion. This is due to the fact that the consumption of primary glass has a positive effect on water resource depletion, i.e. the impacts are negative. Using recycled YOX and other REEs reduces the impacts further, although this impact reduction is very small. This is due to the small quantity of REEs that is used in a lamp, and the fact that not all the REEs that are used can be recycled at the end of life. In fact, in this case study, the end-of-life recycling rate (and the recycled content) for aluminum, mercury and glass was assumed to be near 100% (based on Tan et al. (2015)), while the end-of-life recycling rate – and the recycled content if the materials are used in a closed loop – of YOX is 24%, and the RRE of the other elements is below 10%.

*Is the demand for 1 fluorescent lamp with a high content of recycled YOX less accountable for impacts than the demand for 1 fluorescent lamp that contains a low content of recycled YOX?*

In this analysis, the recycled content of all materials is kept constant (simulating closed-loop recycling), while only the recycled content of YOX is changed from 0%-25%-50%-75%-100%. Figure 7B-28 shows that an increased recycled content of YOX leads to a lower impact attributed to the lamp. The impacts of climate change can be reduced by 20% with an increased recycled content from 0% to 100%.

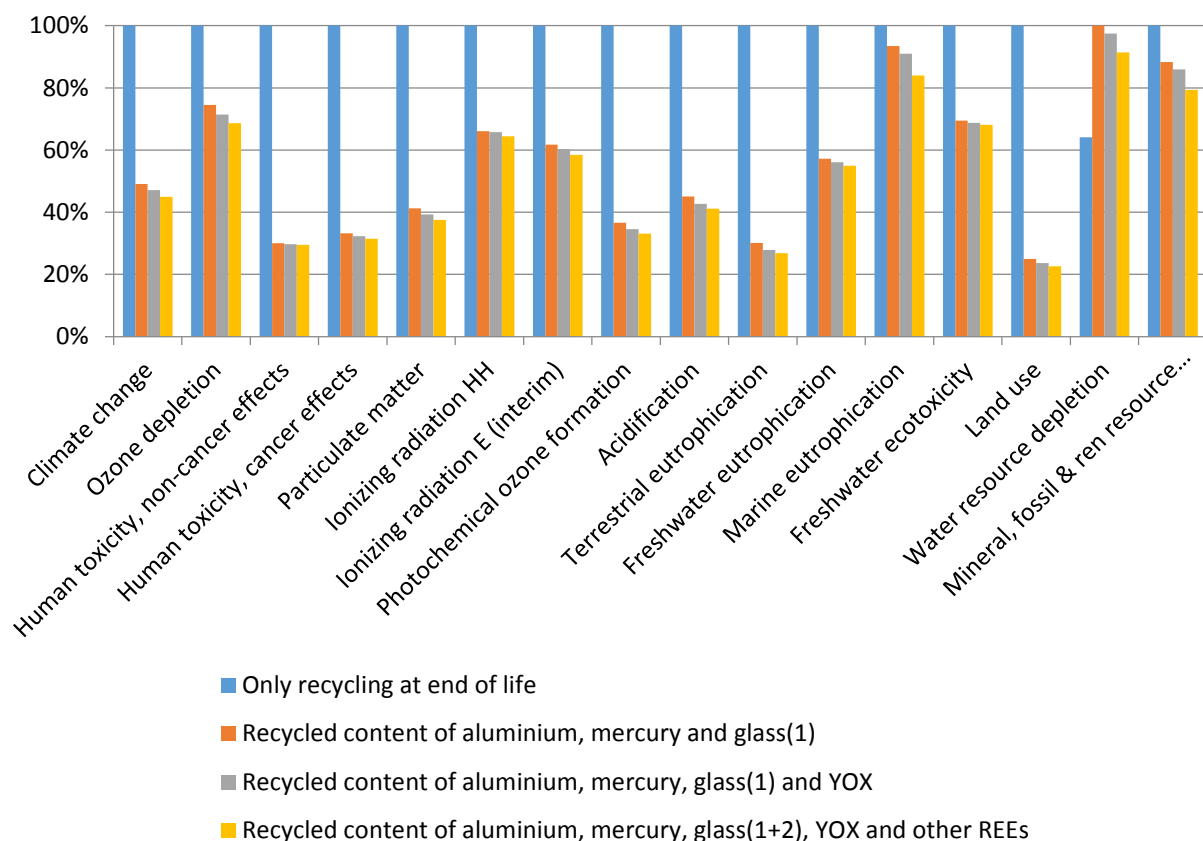


Figure 7B-27 Comparison of the impacts attributed to the demand for 1 fluorescent lamp with a varying degree in which recycled materials are used as recycled content. The results are represented relative to the alternative with the highest impacts, which is set to 100%

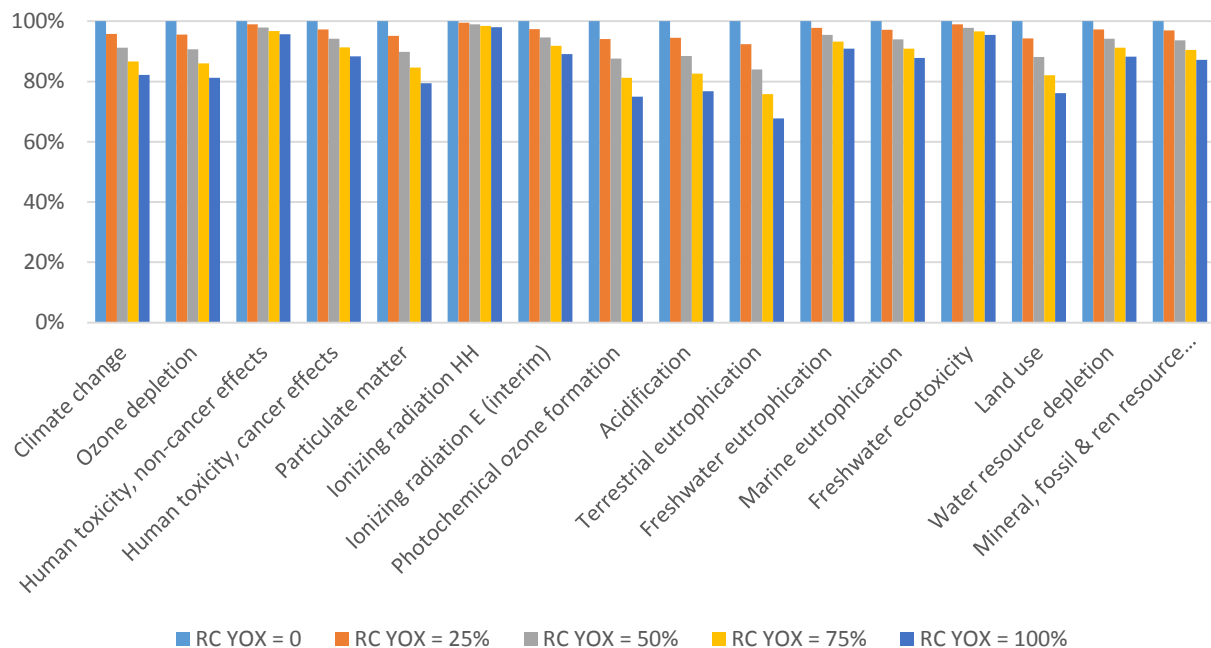


Figure 7B-28 Comparison of the impacts attributed to the demand for 1 fluorescent lamp containing different quantities of recycled YOX. The recycled content (RC) of YOX is varied between 0% and 100%. The recycled content of other recycled materials (glass, aluminum, mercury and other REEs) is kept constant at the level of RC = RRE. The results are represented relative to the alternative with the highest impacts, which is set to 100%

## 5. Discussion

The results of the assessments in this chapter have a limited use due to several reasons. Limitations are caused by the goal and scope definition, by the inventory analysis and by the impact assessment.

### 5.1. Goal and scope definition

During the goal and scope definition of the study, several LCA goals were formulated. During the interpretation, it appeared that each goal definition provides slightly different results. This suggests that the results of one analysis cannot directly be used to make statements on different types of LCA studies with a slightly different goal definition. Therefore, the results are limited to the goal definition for which the analysis was applied.

The same can be said about the scope. This analysis focused on the production of recycled YOX in France, using the current French electricity mix. If the scope would be extended to the production of recycled YOX in a different geographical location or at a different moment in time (either the past or the future), this would influence the collection of data for the inventory. Therefore, the results of this analysis are limited to the scope as formulated in this study.

Finally, the motivation of the LCA studies in this chapter largely influences the LCA as well. In this study, the aim was to identify for what impacts a product or process can be held accountable. Based on this, an attributional LCA was conducted. However, other reasons to undertake an LCA exist as well. For example, one might want to assess what impacts are caused by the additional or decreased production of or demand for a product, due to interactions that take place on the market. This would require a consequential LCA, for which different inventory would be collected. Therefore, the results of this attributional LCA cannot be used to answer the question of what impacts are caused by the recycling process of or the demand for YOX.

## 5.2. Inventory data

The inventory analysis is a large source of uncertainties in the results. Primary data from Solvay were used for the recycling process of YOX (Lartigue-Peyrou 2016). However, the background database ecoinvent 3.2 was used for the intermediate flows entering and exiting the foreground process. Data uncertainties in the background database are a common issue. Besides the uncertainty related to the amounts of flows and allocation factors, it is not certain whether the processes that are included in the database are representative of the actual processes in the supply chain of the recycled YOX.

Not all intermediate flows were available in the ecoinvent database. These had to be modeled separately. This is, for example, the case for the primary production route of REEs from bastnäsite and ionic ore. The degree of uncertainties in these processes is further discussed in the respective publications (Sprecher et al 2014; Vahidi et al 2016). Allocation between the REEs was applied after the separation into individual elements. However, some combination of elements might be already considered to be a co-product. For example, neodymium and praseodymium do not have to be separated further in certain applications (Sprecher et al 2014). A more detailed analysis of the REE market could indicate the correct “point of substitution”. For the separation of heavy REEs from ionic ore, the same inventory was used as for the separation of light REEs from bastnäsite. This is a source of high uncertainty as well. Ideally, a parametrized model is developed of the separation process that could be adapted for REEs mixtures of varying composition. Furthermore, the allocation between iron ore and REE ore potentially influences the results of the impacts attributed to light REEs. As the REOs are a by-product from ionic ore mining (Gupta and Krishnamurthy 2005), it is assumed that the relative revenue for the REO ore does not exceed 20%. For the production of HREEs from ionic ore, the ore composition of the Longnang deposit in China had been used. This influences the allocation factors of the separated REEs. It would be interesting to analyze whether the results would be different if REE concentrate from different mines would be used in the primary production route. For example, europium oxide can be produced from bastnäsite and ionic ore. In this study, europium oxide from bastnäsite was used. To make a representative mix of production routes for each REE, an analysis is required on the relative production volumes of the mines. This is however outside the scope of this study.

In the product-oriented LCA, the number of sources of uncertainty is higher than in the process-oriented LCA. This is due to the fact that the inventory of the REE mix must be identified, and allocation is applied between the co-products of the recycling process. Both the location of allocation – the point of substitution – of the co-products of the recycled fluorescent lamps and the allocation factors are subject to uncertainties. The economic value of the REE mix was set at 60% of the revenue from the co-products. This could be a high estimate. A lower value would lead to lower impacts attributed to the REE mix, hence to the recycled YOX. Finally, the economic values of the co-products that are used to apply allocation are subject to uncertainty. This was already discussed in Chapter 5. The results of a Monte Carlo simulation (presented in Annex II) show that the conclusion that recycled YOX is accountable for lower impacts than primary YOX is robust.

## 5.3. Application of APOS

One of the axioms used in this thesis – “The product system supplying the material that requires waste treatment is responsible for impacts that take place during this treatment” (Axiom 3) – could be interpreted in a slightly different way than applied in this chapter. Here, it was considered that the product system that supplies the material for treatment was the product system of the fluorescent lamp. However, each upstream producer in the product system of the lamp – e.g. the producers of the lamp bulb, the lamp holder, and the metals that are used in these parts – could be considered as “the

product system supplying a material that requires waste treatment”. For example, the producer of the lamp holder could be held responsible for the waste treatment of the lamp holder.

This different perspective results into a different allocation procedure, in which the recycled material becomes a co-product of the first use of the same material. For example, the mix of recycled REEs becomes a co-product of the process that provides the primary mix of LAP and YOX for a first application in the lamp. This procedure has as a consequence that the first user of the material becomes fully responsible for all dismantling activities that are required to produce a useful co-product, even though these activities could be partly considered as a production process for the recycled product. The price of the recycled product could be compared to the price of the primary equivalent, and a price ratio could be established that is more close to 1. This means that the primary material could be responsible for 50% of all primary production steps, and the recycled material for the resulting 50%. This is illustrated in Figure 7B-29. This procedure is also proposed in the ILCD Handbook (European Commission 2010).

The benefit of this approach is that the user of the recycled material is not considered responsible for impacts of a product system that seem unrelated to the second application of the recycled product. For example, the recycled REEs are not responsible for the mercury that is used in the light bulb. This would avoid to model the full manufacturing and waste treatment steps of the previous life cycle<sup>6</sup>.

Although this procedure could have benefits in some situations, it is difficult to apply this procedure consistently to all different types of multifunctionality. In fact, the approach represented by Figure 7B-29 applies a material-centric view on recycling, which focuses on the recovery of specific materials (UNEP 2013). The application of APOS in this case study represents rather a “product-centric view”. According to UNEP, *“a product-centric perspective requires an ability to comprehend the interconnected system of design, collection, sorting and processing that determines the performance of a product’s recycling”* (UNEP 2013). They also state that a product-centric view enables to optimize the recovery of different materials from complex products, while *“considering all factors that affect a system’s outcome, in an attempt to improve this outcome”* (UNEP 2013). Therefore, the product-centric application of APOS – as applied in this case study – is preferred over the material-centric view as represented by Figure 7B-29.

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<sup>6</sup> However, knowledge of processes that take place upstream in the supply chain can be valuable. This is further discussed in Chapter 8.



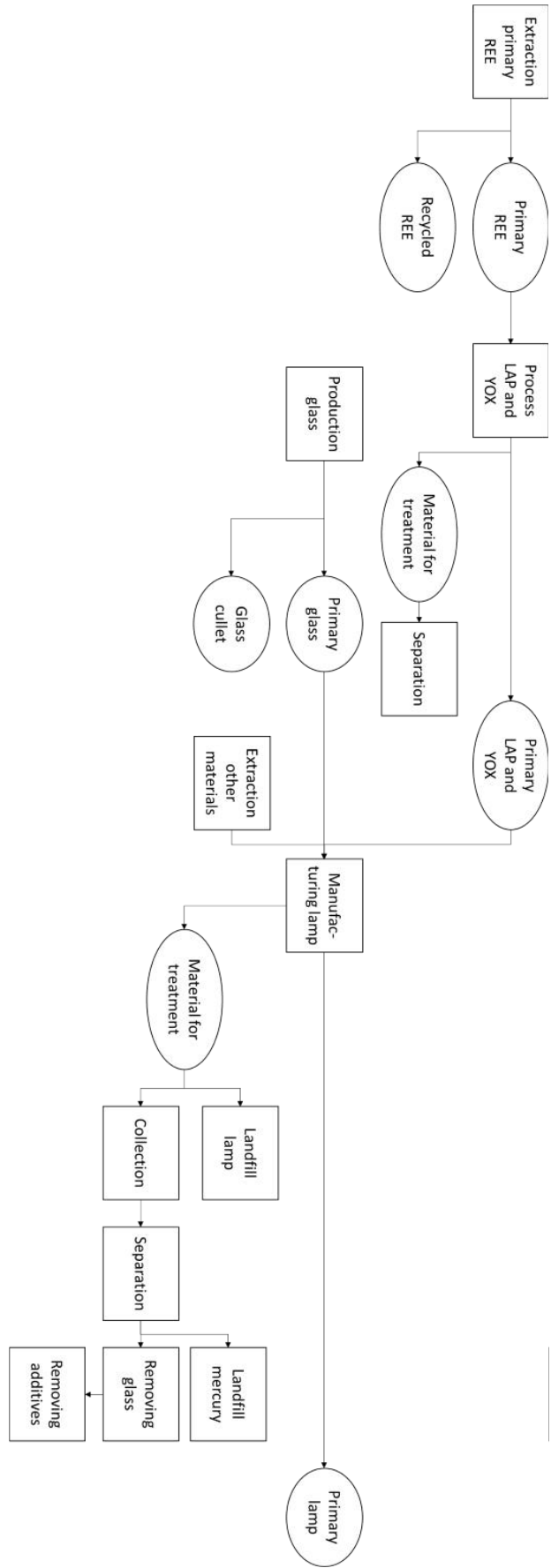


Figure 7B-29 Alternative allocation procedure, in which the recycled product becomes a co-product of the primary production process of this material. This configuration represents a “material-centric view” on recycling

#### 5.4. Impact assessment

In this thesis, we used the impact assessment method ILCD Midpoint 2011 version 1.08. However, other impact assessment methods exist as well. These methods study often similar impact categories, although sometimes different characterization factors are used. This could result in different results and perhaps in different conclusions. Within each modeling method, uncertainties exist related to the assumptions about the responsiveness of ecological processes to the extraction or emission of elementary flows (Huijbregts 1998). Impact assessment methods also rely on value choices (Hertwich et al 2000; Hofstetter et al 2000; De Schryver et al 2011). De Schryver et al. (2011) demonstrate the influence of value choices by calculating different characterization factors for the endpoint human health damage. They apply three different world views of the Cultural Theory (Hofstetter et al 2000): the individualist, the egalitarian and the hierarchist perspectives. Between these perspectives, characterization factors can vary between positive and negative values and differ up to six orders of magnitude (De Schryver et al 2011). Furthermore, there might be some inconsistencies between the inventory of ecoinvent and the impact assessment method, such as the assessment of water resource depletion in the primary production of glass and aluminum.

A large number of elementary flows is not classified in the ILCD method. Some elementary flows are excluded from certain impact categories due to the fact that they were not compliant to ILCD nomenclature (European Commission 2012). A list of these elementary flows should be included together with the results of the impact assessment (ISO 2006a). Due to a large number of analyses that is done in this case study and the illustrative purpose of this chapter with regard to the allocation procedure, no further consideration is given to unclassified elementary flows.

#### 6. Conclusions

This chapter presents an attributional case study on the recycling of rare earth elements from fluorescent lamps. Based on the elements of the systematic framework of Chapter 3, 11 research questions were formulated that represent archetypes of LCA goal and scope definitions. These goal and scope definitions all aim to identify the accountability of impacts of the recycling process of YOX, the product “recycled YOX” as well as the impacts of a lamp that uses recycled YOX.

The process-oriented LCA showed that the valorization process of YOX and other REEs from used fluorescent lamps is accountable for much lower environmental impacts than the primary production route of these materials. The contribution analysis showed that the impacts of the recycling process are mainly caused by the treatment of the phosphorous powder. This would be a good starting point if the impacts of the process must be reduced.

Allocation was applied to calculate the impacts that can be attributed to recycled YOX in a product-oriented LCA. It appeared that the main contributor to the impacts of recycled YOX is the use of the REE mixture from used fluorescent lamps, which carries impacts related to the product system of the lamp. It could be more difficult to reduce these impacts, due to the fact that the product system of the fluorescent lamp is outside the sphere of influence of a company that only produces REEs. Impacts might be reduced by identifying other sources of recycled REEs than fluorescent lamps. However, a user of recycled YOX is already accountable for lower impacts than a user of primary YOX. Furthermore, if a REE producer decides to produce more recycled YOX at the expense of primary YOX, the impact profile of the company would be improved.

Nevertheless, a fluorescent lamp that is involved in the valorization of phosphorous powder to recycle YOX is not accountable for lower impacts than a lamp that is not recycled. Impacts of a lamp can be mainly decreased by the use of recycled aluminum, mercury, and glass. The fact that the consumption of REEs in quantities that reflect a closed loop does not affect the impacts of the lamp is due to the low

end-of-life recycling rates of the REEs. It is shown that a high recycled content of YOX improves the environmental profile of the lamp.

From the goal and scope definition of Chapter 7A, archetypes of attributional goals and scopes were distilled. The systematic framework showed that, in these types of goal and scope definitions, multifunctional situations could be solved by system expansion or partitioning. The case study of this chapter demonstrated that these allocation procedures can indeed be applied to recycled materials in an attributional LCA and provide relevant results. The partitioning method that was developed in Chapter 5 appeared to be applicable to co-production and recycling, and the step-by-step guidance in that chapter proved to be useful to apply the APOS method. It has been demonstrated how the equations of Chapter 5 are applied. Furthermore, the market-price ratio  $A$  that identifies demand constraints in consequential LCA proved also useful in this attributional LCA. This factor was used to determine the comparability of two product systems in the process-oriented LCA.

From the impact assessment, it appeared that different types of results were generated for each goal definition. However, it should be acknowledged that the results have several limitations. The goal and scope phase has influenced the inventory collection of the LCA. Therefore, the results cannot be used in other LCA studies with different goal and scope definitions. During the inventory collection, several sources of uncertainties could be identified, related to the processes that were chosen in the background, as well as to the data that were used to apply allocation. However, an uncertainty analysis indicated that the conclusions of the study are robust. Also the impact assessment methodology is a source of uncertainty, which is not further discussed in this thesis.

The results from the APOS method are sometimes difficult to interpret, as some impacts seem unrelated to the product under study. However, it is aimed in this thesis to identify an allocation procedure that provides relevant results for industrial objectives. Therefore, the interpretation of the results from this attributional LCA study in an industrial context is further discussed in Chapter 8.

## Chapter 7C: Consequential LCA on the recycling of rare earth elements from end-of-life fluorescent lamps

### 1. Introduction

In Chapter 7B, an attributional LCA was applied to the valorization of YOX from used fluorescent lamps. In this Section C of Chapter 7, the same case study is analyzed by a consequential LCA. For this, the theoretical contribution to consequential LCA developed in Chapter 6 is applied: a causal loop diagram is used to identify the affected process of a changing demand or production of a product. It is considered that some elements are stockpiled, or can be supplied from stockpiles. The market-price ratio between a recycled product and a primary product is used to identify whether the demand for the recycled product is constrained, or whether downstream effects might take place due to the substitution. Furthermore, a single modeling method is applied to all situations of recycling and co-production, considering the fact that substitution might not always take place on a material level, but can also take place on a system level.

The goal and scope definition of this consequential LCA has been presented in Chapter 7A. Main parameters that influence the modeling method are summarized in Table 7C-1. From these parameters, archetypical consequential goal and scope definitions are formulated, on which the consequential case study of this chapter is based.

### 2. Archetypes of consequential LCA goal and scope definitions

In this section, the research questions are formulated that form the basis of the consequential LCA study. Similar to the attributional case study of Chapter 7B, the elements of Table 7C-1 are applied to the research questions of the text box of “Archetypical LCA goal and scope definitions”.

Table 7C-1 Summary of parameters that contribute to archetypical consequential LCA studies. The terms represented by  $\alpha$ ,  $\beta$ , and  $\gamma$  are used in the archetypical goal and scope definitions as defined in the box below

Item of the goal and scope definition	LCA approach	Building blocks of archetypical goal and scope definitions	
The perspective of the LCA	Consequential LCA	$\alpha$	$\alpha$ : Consequences on global impacts
The reason to conduct the study	Process-oriented LCA	$\beta$	$\beta$ : The production / treatment
	Product-oriented LCA		$\beta$ : The demand
The functional unit	Substitution	$\gamma$	$\gamma$ : 1 kg of recycled YOX ready for shipment $\gamma$ : 1 fluorescent lamp
	System expansion		$\gamma$ : 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of residual recycled europium and 9.92 kg of phosphorous powder from used fluorescent lamps

### Archetypical consequential LCA goal and scope definitions

- **Quantifying environmental impacts:**
  - What is/are the  $\alpha$  of  $\beta$  of/for  $\gamma$ ?
- **Identifying opportunities for improvement:**
  - How can we decrease the impacts of  $\beta$  of/for  $\gamma$ , in order to decrease the  $\alpha$ ?
- **Decision-making:**
  - *Global impacts:* Does  $\beta$  of/for  $\gamma$  have (a) lower  $\alpha$  than its alternative?

The archetypes of LCA goal and scope definitions can now be expressed in the form of the following research questions:

- Process-oriented LCA:
  - What environmental impacts are caused by the production of 1 kg of recycled YOX from phosphorous powder?
  - What environmental impacts are caused by the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps?
  - How can we reduce the environmental impacts of the production of 1 kg of recycled YOX from phosphorous powder, in order to reduce global impacts?
  - Does the production of 1 kg of recycled YOX from phosphorous powder have lower consequences on global impacts than the production process of primary YOX?
- Product-oriented LCA on recycled YOX:
  - What environmental impacts are caused by the demand for 1 kg of recycled YOX?
  - How can we reduce the environmental impacts of the demand for 1 kg of recycled YOX, in order to reduce global impacts?
  - Does the demand for 1 kg of recycled YOX cause less environmental impacts than the demand for 1 kg of primary YOX?
- Product-oriented LCA on a fluorescent lamp:
  - What environmental impacts are caused by the demand for 1 fluorescent lamp?
  - How can we reduce the environmental impacts of the demand for 1 fluorescent lamp, in order to reduce global impacts?
  - Does the demand for 1 fluorescent lamp that contains recycled YOX and valorizes the phosphorous powder at the end of life cause less environmental impacts than the demand for 1 fluorescent lamp that only valorizes the phosphorous powder at the end of life or the demand for 1 fluorescent lamp that is not involved with the valorization process at all?

### 3. Inventory analysis

To model the effects of the additional production of a process or the additional demand for a product according to the Causal Loop Diagram of Figure 6-5, the step-by-step guidance for process-oriented and product-oriented LCAs is applied (Figure 7C-2 and Figure 7C-3). Note that the guidance for the two approaches is closely related. The main difference is the starting point: in a process-oriented LCA, the process under study is already known, while the relevance of the co-products is not. In a product-oriented LCA, the product is known, while the process that supplies this product is not yet identified. During the analysis, we have to switch between process-oriented and product-oriented approaches, for example when a process requires the consumption of intermediate input flows. Equation E1 has



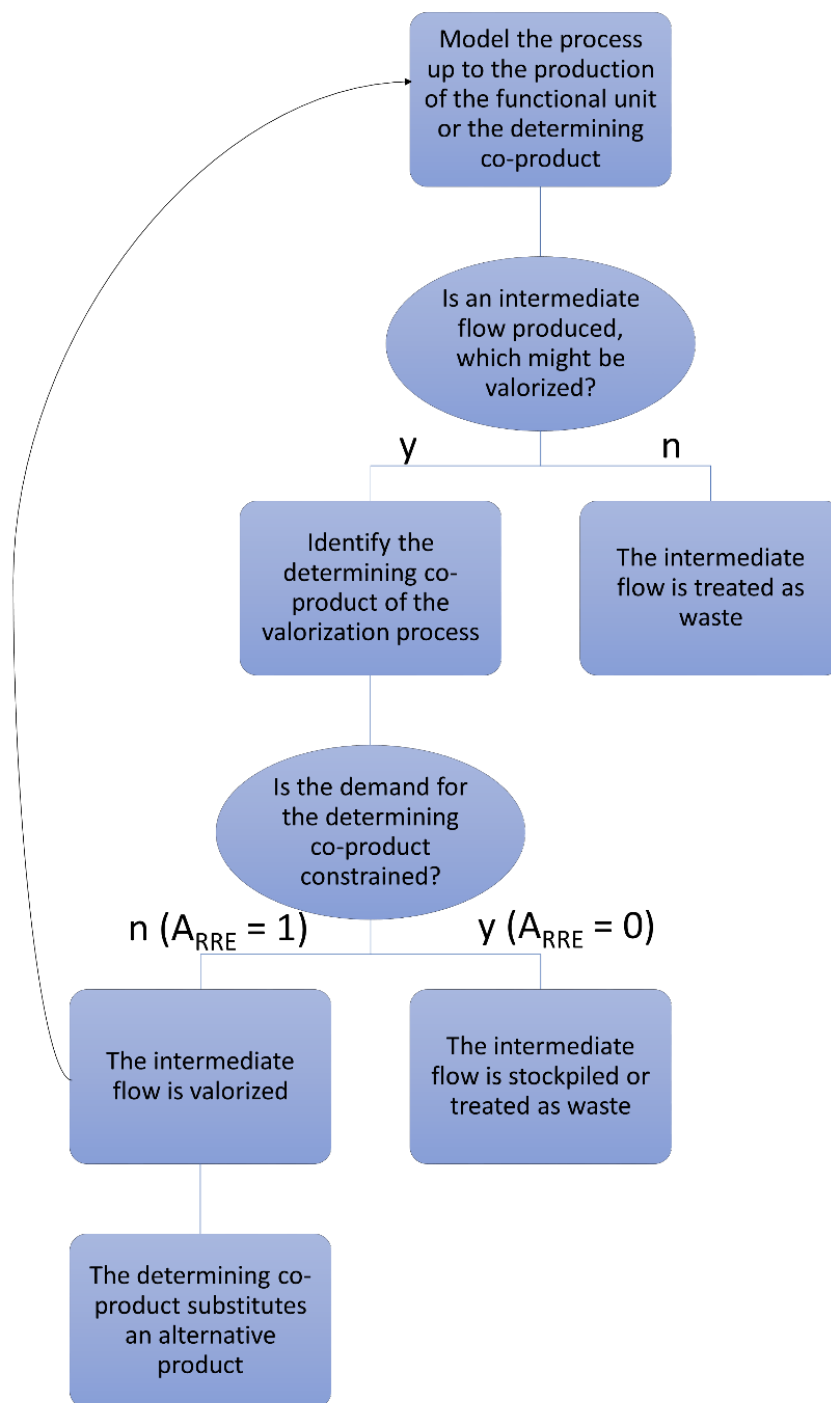


Figure 7C-2 Step-by-step guidance for an LCA in which the starting point is a process

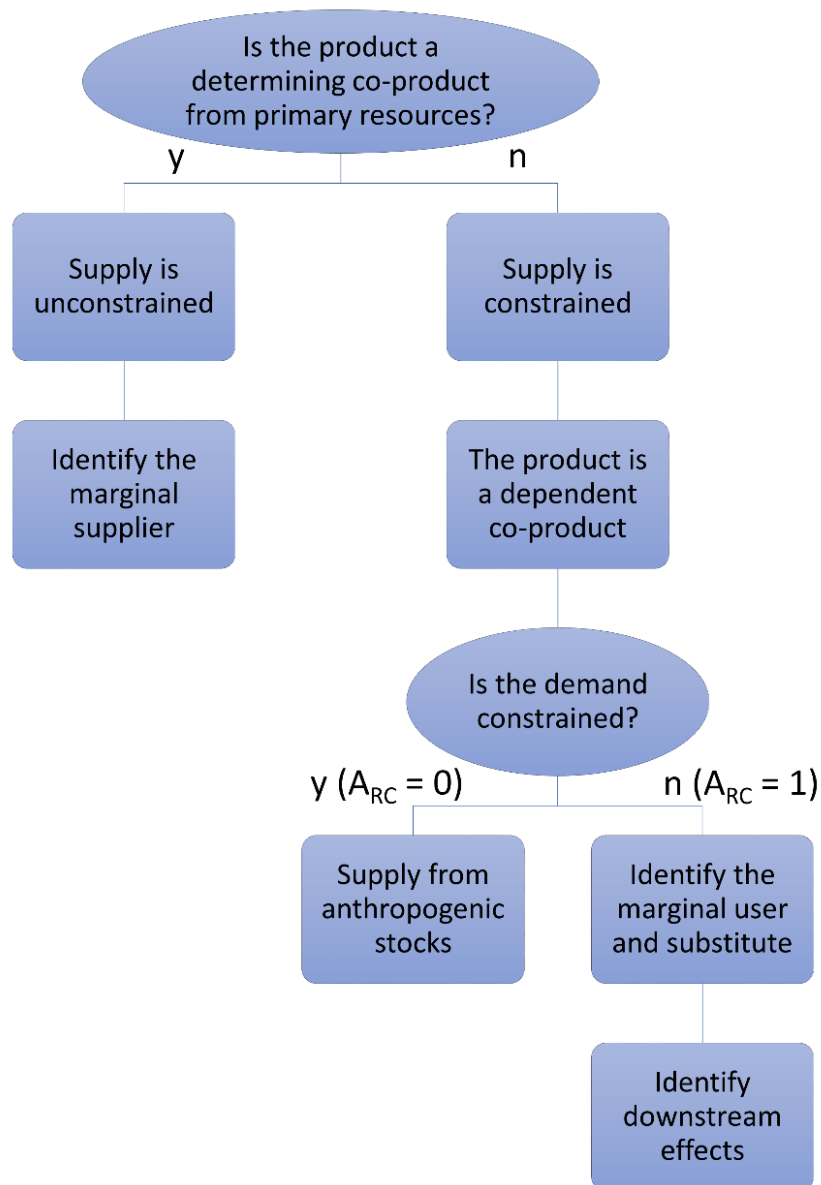


Figure 7C-3 Step-by-step guidance for an LCA in which the starting point is the demand for a product



$$\begin{aligned}
 E1. \quad E_{tot} = & \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{(1 - A_{RC_i})}{C_{RC_i}} * \right. \\
 & \left. (E_{RC_i} - E_{d_i}^*) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \\
 & \left. \sum_{i=1}^n RI_i * RRE_i * \left( (1 - A_{RRE_i}) * E_{d_i} + A_{RRE_i} * \left( E_{RRE_i} + C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * (\Delta E_{\alpha_i}^* - E_{v_i}^*) \right) \right) \right)
 \end{aligned}$$

Table 7C-2 Legend of terms for Equation E1

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI / unit of analysis
$i$	Refers to an intermediate flow, recycled material or co-product that is used or produced in the life cycle of the product under study	
$Q$	Total quantity of an intermediate flow (recycled plus primary) used per unit of the product under study	Rate $\geq 0$
$RI$	Production rate of the intermediate flow that is (partly) valorized 1) per unit of the product under study or 2) per unit of material entering the valorization process	Rate $\geq 0$
$E_{\alpha}$	LCI due to the downstream impacts related to the use of the material in the functional unit	$E_{\alpha_v} + \Delta E_{\alpha}$
$E_{\alpha_v}$	LCI due to the downstream impacts if only primary material were used	LCI / unit of analysis
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the life cycle under study	LCI / unit of displaced primary material
$\Delta E_{\alpha}^*$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the subsequent life cycle	LCI / unit of displaced primary material
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{RC}$	LCI due to the recycling process related to the recycled content (including LCI of material losses during the recycling process)	LCI / unit of input material
$E_{RRE}$	LCI due to the recycling process related to the recycled material produced at the end of life (including LCI of material losses during the recycling process)	LCI / unit of input material

Term	Explanation	Value
RC	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
RRE	End-of-life recycling rate (recycled or recovered material collected at the end-of-life divided by the available material after the use phase)	$0 \leq \dots \leq 1$
$C_{RC}$	Conversion efficiency of the recycling process related to the recycled content	Unit of useful output / unit of input material
$C_{RRE}$	Conversion efficiency of the recycling process related to the end-of-life recycling rate	Unit of useful output / unit of input material
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$Q_{RRE}/Q_v^*$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})}{(P_v + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})} * (Q_{RC}/Q_v)^{-1}$
$A_{RRE}$	Market-price ratio between the recycled material and the displaced primary material in the subsequent life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})}{(P_v + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})} * (Q_{RRE}/Q_v^*)^{-1}$

### 3.1. Process-oriented LCA

First, it is demonstrated which terms of Equation E1 are relevant in this process-oriented LCA. Then, the consequences of the production of recycled YOX from phosphorous powder are assessed by the steps of Figure 7C-2. This inventory is collected for the functional unit of the production of 1 kg of recycled YOX. If the demand for other products is affected by the additional production of YOX, the consequences are assessed by the steps of Figure 7C-3.

#### 3.1.1. Mathematical approach to calculating the consequences of the production of recycled YOX

Several terms of Equation E1 refer to the effects of the additional demand for a product. However, in the process-oriented LCA, the additional production of a process is the topic of interest. The terms that are not relevant in this analysis are indicated in light gray in Equation E2. A graphical representation of the parameters of Equation E2 is given in Figure 7C-4. During the recycling process of YOX, other co-products are produced as well. The consequences of this co-production are in principle calculated by the blue terms of Equation E2. However, an additional term is added as well: the term in red can be applied when inventory is unknown. This term is part of the “simplified formula for missing inventory

data” (Equation E25 of Chapter 6). The parameters are further explained in the next section. Finally, an overview of the values that are used in Equation E2 is given in Table 7B-7.

$$\begin{aligned}
 E2. \quad E_{tot} = & \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{(1 - A_{RC_i})}{C_{RC_i}} * (E_{RCYOX} - \right. \\
 & E_{d_{powder}}^*) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \left. \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \sum_{i=1}^n RI_i * \\
 & RRE_i * \left( (1 - A_{RRE_i}) * E_{d_i} + A_{RRE_i} * \left( E_{RRE_i} + C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * (\Delta E_{\alpha_i}^* - E_{v_i}^*) \right) \right) + \\
 & \sum_{i=1}^n RI_i * RRE_i * \left( E_{RRE1_i} - A_{RRE_i} * C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * E_{v_i}^* \right)
 \end{aligned}$$

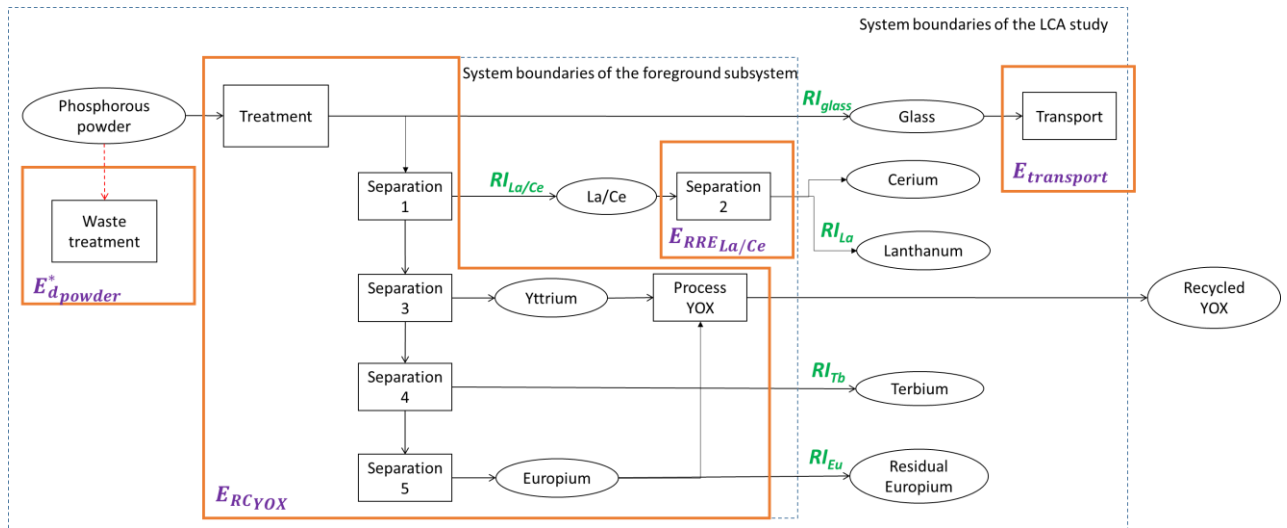


Figure 7C-4 Valorization process of phosphorous powder into recycled YOX. Glass, La/Ce, terbium and an excess of europium are intermediate flows, which are considered in “supply dependent co-product” in the CLD

### 3.1.2. Consequences of a changing production of a process

The consequences of the production of recycled YOX from phosphorous powder are assessed by the steps of Figure 7C-2.

#### 3.1.2.1. Model the process up to the production of the functional unit or the determining co-product

The production of recycled YOX is the functional unit. Therefore, the valorization process contains all process steps that are required to create 1 kg of YOX, including the consumption – and the avoided waste treatment – of the phosphorous powder. These processes are indicated by the boxes referring to  $E_{RCYOX}$  and  $E_{d_{powder}}^*$  in Figure 7C-4. The alternative waste treatment route for phosphorous powder that was used in Chapter 7B is also available in the consequential system model of ecoinvent 3.

#### 3.1.2.2. Is an intermediate flow produced, which might be valorized?

Besides the determining co-product “recycled YOX”, several additional intermediate flows are generated during the valorization of the powder. These flows are “Glass”, “La/Ce” (the mix of lanthanum and cerium), “Terbium” and “Residual europium” in Figure 7C-4.

#### 3.1.2.3. Identify the determining co-product of the valorization process

For each of these intermediate flows that have the potential to be valorized, it is now identified whether they will indeed be valorized or treated as waste instead. No additional valorization processes

are associated with terbium and europium. The valorization of glass cullet only produces glass, which is the determining co-product. The intermediate flow “La/Ce”, coming from Separation 1, could be further valorized in Separation 2 to produce recycled lanthanum and recycled cerium. As two co-products can be produced, the determining co-product of this separation step should be identified. If the revenue of either lanthanum or cerium would be sufficient to cover the marginal operating costs of the separation activity, cerium would be the determining co-product, as this product has a higher normalized market trend. As a consequence, lanthanum is produced as a dependent co-product of the production of cerium by Separation 2.

#### 3.1.2.4. Is the demand for the determining co-product constrained?

The market-price ratio  $A$  is used to indicate demand constraints for the recycled glass, cerium, lanthanum, terbium and residual europium.

##### 3.1.2.4.1. Demand constraints for glass

In this case study, it is assumed that the glass cullet can be used in the primary production route of glass products. The price of glass cullet was already identified in Chapter 7B, which served in the economic allocation of the co-products of the fluorescent lamp. This price was determined to be 0.34 \$/kg. From UNdata (2016), prices can be obtained for “Glass envelopes (bulbs & tubes) for electric lighting”. The average price for France and EU28 between 2010-2015 is calculated to be 4.80 \$/kg. It is acknowledged that these prices are determined after several production steps, compared to where the recycled glass cullet enters the production system. Figure 7C-5 shows the cradle-to-cradle system of container glass. This glass is not the same as the glass from this case study, although the figure could help to understand how glass cullet could be used. It can be understood that the glass cullet cannot directly replace a glass tube, but it could rather substitute some of the raw materials entering the production process. We assume in this chapter that the recycled glass will be absorbed by the market and the lower price for glass cullet than the price for the finished product can be explained by the additionally required production steps. Ideally, it should be identified what raw materials are actually displaced by the cullet. Then, the market-price ratio could be based on these raw materials, instead of the final glass tube. Even if these primary materials are identified, it might be possible that the glass cullet has a higher price than the substituted materials. This could be explained by the fact that the use of glass cullet instead of virgin materials could give benefits during the manufacturing process, e.g. a reduced consumption of energy (GPI 2010). Therefore, to make glass cullet fully comparable to the displaced products, these indirect downstream effects should be quantified and included in the calculation of  $A$ . This would require an LCA – and ideally also a Life Cycle Costing analysis to provide price data for the calculation of  $A$  – that compares a glass production process using only primary materials to a process that also uses glass cullet. Although this case study would benefit from this additional data, the collection of this data is considered outside the scope of this current work, which primarily focuses on the demonstration of the modeling procedure.

If the impacts of the additional production steps and downstream benefits of using the glass cullet are assumed to be linearly related to the price and to the inventory of a primary glass tube, the simplified formula (Equation 24 of Chapter 6) could be applied. This follows from the decision tree of Figure 7C-6, which summarizes the interpretation of the market-price ratio of recycled glass and primary glass. The transport to the glass factory can be fully modeled in the recycling system of YOX, while the additional process steps are modeled by the user of the glass. The value for  $A$  is now 0.07, which means that the recycling system of YOX models the transport and 7% avoided production of primary glass tubes. No waste treatment is modeled, as it is assumed that there are no demand constraints besides the additional processing of the glass cullet.

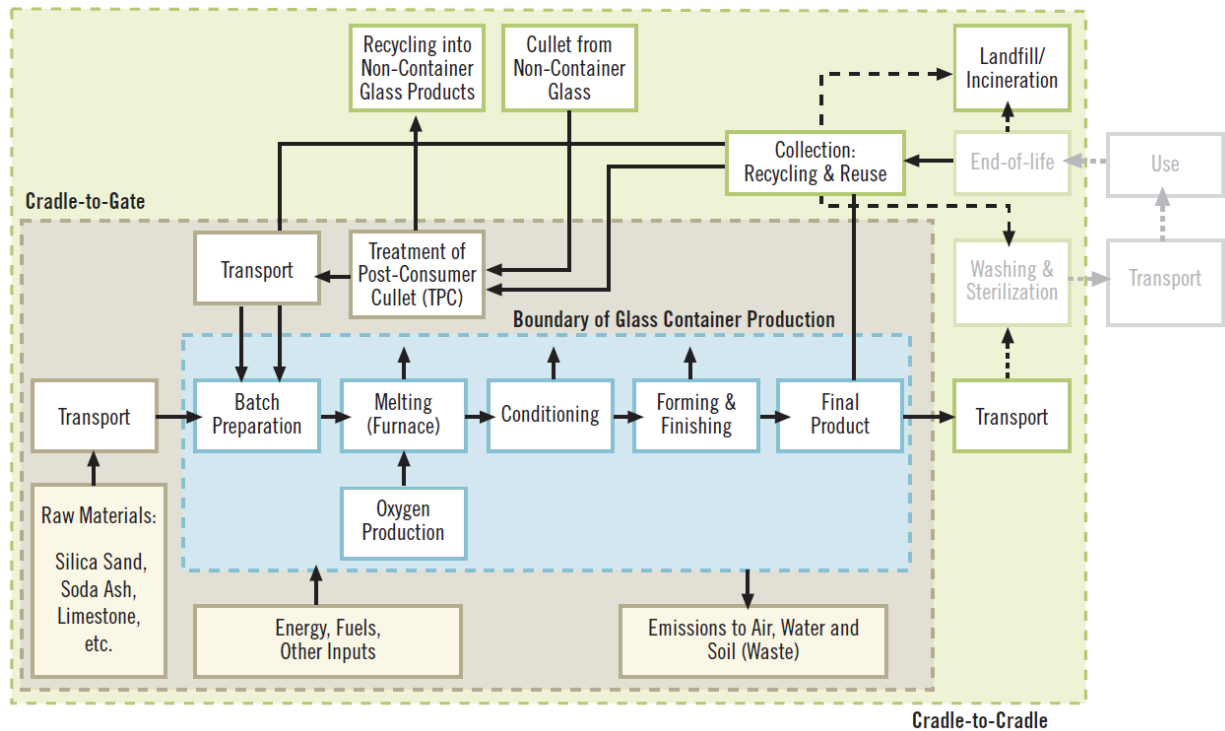


Figure 7C-5 Life Cycle Flow diagram for container glass from cradle to cradle (GPI 2010)

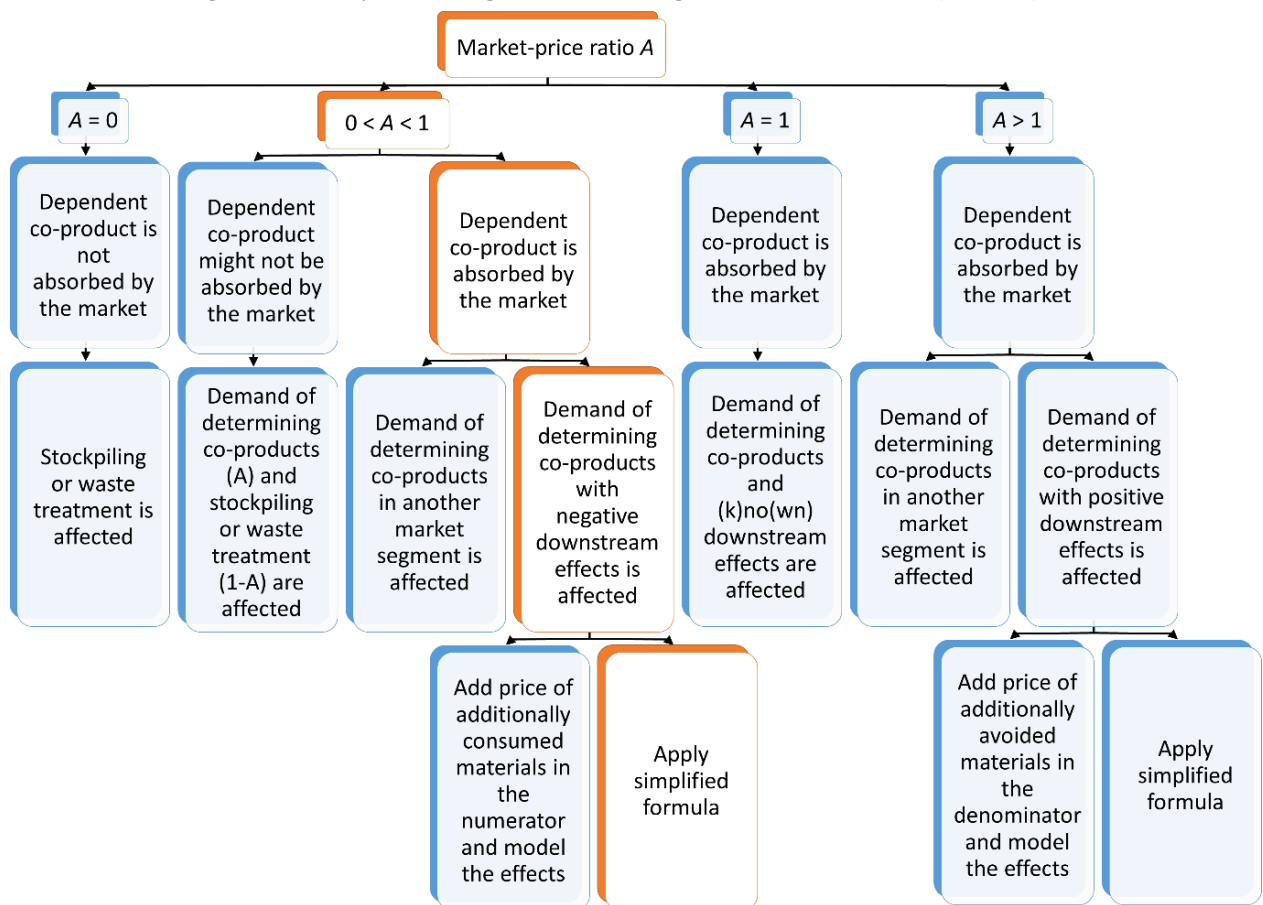


Figure 7C-6 Interpretation of the market-price ratio of glass cullet and glass tube

### 3.1.2.4.2. Demand constraints for rare earth elements

It is assumed that the recycled cerium has the same market price as primary cerium oxide. This means that there are no demand constraints for recycled cerium compared to primary cerium, and the recycled cerium can be valorized and substitute primary cerium. It is discussed below what impacts are actually avoided in this case. The same assumption is done for the other recycled REEs and their primary equivalents.

### 3.1.2.5. The determining co-product substitutes an alternative product

Several products have now been identified that could be substituted by co-products of the valorization process: primary glass, cerium, lanthanum, terbium and europium. This means that the process-oriented LCA now becomes a product-oriented LCA where the consequences of a changing demand for these products must be analyzed. Up to now, the substituted primary products have been referred to by the parameter  $E_v^*$ . However, this parameter represents the situation in which the supply of the substituted primary product is unconstrained – which is not the case for all primary materials. Therefore, the consequences of a decreased demand for the products represented by  $E_v^*$  in Table 7B-7 are assessed in more detail in the next section.

Table 7C-3 Summary of values for the parameters of Equation E2

	Glass	La/Ce (Determining co-product Ce)	La	Tb	Eu
RI	2.05	0.18+0.14	0.18	0.07	0.0029
RRE	1	1	1	1	1
$A_{RRE}$	0.07	1	1	1	1
$E_{RRE}$	$E_{transport} + E_{processing} - \Delta E_{electricity}^*$	$E_{RRE,La/Ce}$	0	0	0
$C_{RRE}$	1	1	1	1	1
$Q_{RRE}/Q_v^*$	1	1	1	1	1
$\Delta E_{\alpha}^*$	Unknown	0	1	0	0
$E_v^*$	Glass	Cerium	Lanthanum	Terbium	Europium
Simplified formula	Yes	No	No	No	No
$E_{RRE1}$	$E_{transport}$				

### 3.1.3. Consequences of a changing demand for a product

In this section, the consequences of a decreased demand for primary glass, cerium, lanthanum, terbium and europium is assessed by following the steps of Figure 7C-3. A summary of the findings in this section is given in Table 7C-7.

#### 3.1.3.1. Is the product a determining co-product from primary resources?

Primary glass is the only co-product – and therefore the determining co-product – of the production of glass, which is represented by the dataset “glass tube, borosilicate” in the ecoinvent database. Further analysis is required to identify the marginal suppliers of the substituted REEs. In Chapter 5, it was already stated that primary REEs from the Bayan Obo mine are included in the database of ecoinvent. Therefore, in theory, it would be possible use the consequential system model to model the demand for light REEs. However, in Chapter 5 it was also mentioned that Bayan Obo produces LREEs as a by-product from iron mining. Due to the fact that the revenue for REEs is not necessary to sustain

the mining for iron (Gupta and Krishnamurthy 2005), iron can be identified as the determining co-product of the mining in the Bayan Obo deposit. The demand for REEs will not lead to extra mining from this deposit, i.e. the supply is assumed to be fully constrained. The challenge now is to identify the marginal supplier of each REE that can be displaced due to the recycling process of YOX. For this purpose, first, it is assessed which REEs are determining co-products of primary production routes. As this analysis is quite detailed, a summary of Sections 3.1.3.1.1 – 3.1.3.1.4 is given after in the text box after Section 3.1.3.1.4.

#### 3.1.3.1.1. Identify the determining co-products of primary production routes of rare earth elements

Due to the small concentrations in which REEs appear in rare earth deposits, REEs are in most cases produced as a co-product or a by-product of other minerals. In mines like these, REEs are produced from the REE-rich tailings of the mining activities (Krishnamurthy and Gupta 2015). REEs are the primary product from the Mountain Pass mine in California, from mines in Sichuan and the ion adsorption-type ores in China. Also the Mt. Weld, Yangibana and John Galt deposits in Australia (have the potential to) produce REEs as the main product (Long et al 2010; Krishnamurthy and Gupta 2015). The determining co-product of each of the mines that produce REEs as the main output is identified according to the procedure outlined by Weidema et al. (2009), Consequential-LCA (2015a), Consequential-LCA (2015b), and Consequential-LCA (2015c). The results are shown in Table 7C-4. The revenue for each mine is calculated by the REO content of the mine and the market prices of 2013 (Statista 2016a). The marginal production costs are estimated to be 80% of the total revenue (Consequential-LCA 2015a). The determining co-product is one of the products that must be produced to cover the marginal production costs and which has the lowest normalized market trend (Consequential-LCA 2015b). The data that are used for this analysis are presented in Annex III. Table 7C-4 shows that only neodymium, yttrium, and dysprosium are determining co-products of mines that are expected to change their output with an increased demand for REEs. Although this approach is highly speculative, the results correspond to what could be intuitively expected.

A side-note is required for the determining co-product of the Mount Weld deposit in Australia. The procedure of Consequential-LCA (2015a) learns us that lanthanum is the determining co-product of this mining activity. This is the case under the assumption that the marginal operating costs are 80% of the total revenue. However, the determining co-product is neodymium if the marginal operating costs are 78% of the total revenue. The mining company highlights that NdPr (the mix of neodymium and praseodymium) is their most significant product and that prices for NdPr have remained low (Lynas Corporation LTD 2016). Neodymium is chosen here due to the expected increase in price compared to the relatively stable price for lanthanum (Statista 2016b; Statista 2016c). Considering the fact that the mine is not yet profitable (Lynas Corporation LTD 2016), the revenue of all elements is currently required. Although currently there is a small surplus of neodymium, the market is expected to stay tight and the material has been identified as critical, while the surplus for lanthanum is expected to increase (European Commission 2014a). Among the critical elements of the mine, neodymium has the lowest normalized market trend. Therefore, it could be justified that neodymium is considered to be the determining co-product of the Mount Weld deposit.

#### 3.1.3.1.2. Identify the marginal supplier of the determining co-products

Among the mines that supply neodymium as a determining co-product, it should be identified which producer has the lowest long-term operation costs. This would be the marginal supplier (Weidema et al 2009; Kätelhön et al 2015). The marginal supplier could also be a mix of these producers. More knowledge on the characteristics of each mine is necessary to identify the marginal supplier in a systematic way. The identification of the marginal supplier influences the inventory related to the



Table 7C-4 Determining co-product of REE mining from mines that produce REEs as the main output

Mine	Current status of operation	Determining co-product
Mountain Pass, US	Shut down <sup>4</sup>	Lanthanum
Xunwu, Jiangxi, China	Operating	Neodymium
Longnan, Jiangxi, China	Operating	Yttrium <sup>5</sup>
Southeast Guangdong, China	Operating	Dysprosium
Yangibana, Australia	Start production 2018 <sup>1</sup>	Neodymium
John Galt, Australia	Exploration <sup>2</sup>	Dysprosium
Mount Weld, Australia	Operating	Neodymium <sup>3</sup>

<sup>1</sup>(Mining Technology 2016)

<sup>2</sup>(Northern Minerals 2015)

<sup>3</sup>With the assumption that the marginal operating costs are 80% of the revenue, lanthanum is the determining co-product. See text for explanation.

<sup>4</sup>(GlobeNewswire 2015)

<sup>5</sup>If marginal operating costs are 79.6% of the revenue, erbium is the determining co-product.

mining activity, as well as the composition of the mine, hence the production of co-products. For illustrative and pragmatic reasons – due to the fact that inventory for ionic-ore mining is available (Vahidi et al 2016) – it is assumed that the Xunwu, Longnan and the Southeast Guangdong deposits are the marginal suppliers for neodymium, yttrium, and dysprosium, respectively. The marginal suppliers of neodymium, dysprosium, and yttrium are all deposits of ionic ore. Therefore, for these production routes, the data of Vahidi et al. (2016) is used. The dataset is converted to a consequential dataset by changing each intermediate flow to a flow from the consequential system model of ecoinvent. It is assumed that the inventory of the mining process for each site is the same. Only the elementary flows of REEs are adjusted to the composition corresponding to each mine. Ammonium sulfate is used as an input of the mining process. This is a dependent co-product of caprolactam. In Chapter 6 it was stated that the demand for ammonium sulfate is constrained, i.e. there is currently a surplus. It is assumed that there are no impacts related to the stockpiling of ammonium sulfate, and the additional demand for this product only leads to additional transport. This is modeled by the ecoinvent dataset “market for ammonium sulfate”, which is adapted to only include the transportation processes.

### 3.1.3.1.3. Identify demand constraints of dependent co-products

In this section, we determine whether any of the REE co-products might have demand constraints – i.e. which co-product might not be absorbed by the market. The market situation for all REEs has been analyzed by European Commission (2014) and is summarized in Table 7C-5. In Chapter 6 it was stated that demand constraints are more dominant over supply constraints for dependent co-products that are produced in surplus, hence  $A = 0$ . If a shortage exists for a dependent co-product, supply constraints dominate over demand constraints and  $A = 1$ .

Table 7C-5 shows that there is a surplus of lanthanum, cerium, praseodymium, samarium, gadolinium, holmium, erbium, thulium, ytterbium and lutetium. These materials cannot substitute a determining co-product from a primary production route. The demand for these materials by their marginal user is already satisfied, which has led to the existence of stockpiles. Any additional production of these materials will lead to an increased surplus. Therefore, these materials can be supplied from anthropogenic stocks (i.e. stockpiles).

Although neodymium, dysprosium, and yttrium are also determining co-products of primary production routes, they are included in Table 7C-5 because these elements are produced as dependent co-products in other mines. These elements have a value of  $A = 1$ , due to the fact that they have the



same characteristics in their “dependent” and “determining” form, i.e. each dependent co-product could substitute a determining co-product and users will not notice the difference between the supply routes. Furthermore, in the long term, there is no surplus expected for these elements.

Europium and terbium are not produced in surplus, while they are not determining co-products from a primary production route either. An additional availability of these materials will lead to an increased use by their marginal user. The marginal user is the application that can most easily use an alternative material if the price of one of these materials becomes too high.

Table 7C-5 Market situation of the REEs that are dependent co-products (European Commission 2014a)

Rare Earth Element	Current situation	Market outlook (2020)	A-value
Lanthanum	Surplus	Surplus	0
Cerium	Surplus	Surplus	0
Praseodymium	Surplus	Surplus	0
Neodymium	Surplus	Tight	1
Samarium	Large surplus	Large surplus	0
Europium	Shortage	Shortage	1
Gadolinium	Surplus	Surplus	0
Terbium	Surplus <sup>a</sup>	Shortage	1
Dysprosium	Surplus	Tight	1
Holmium	Large surplus	Large surplus	0
Erbium	Surplus <sup>a</sup>	Surplus	0
Thulium	Large surplus	Large surplus	0
Ytterbium	Large surplus	Large surplus	0
Lutetium	Large surplus	Large surplus	0
Yttrium	Shortage	Shortage	1

<sup>a</sup>The report of the European Commission (2014) is not conclusive about the market situation of terbium erbium. The text of the report indicates a significant surplus, while a graph shows a current shortage of both elements and a small surplus for erbium and a shortage for terbium in 2020.

#### 3.1.3.1.4. Supply from anthropogenic stocks for dependent co-products with demand constraints

Some of the REEs can be supplied from stockpiles. However, additional impacts could be related to this supply. Elements could be stockpiled in separated form, or in combination with other elements. Therefore, the supply of some elements might require additional separation. In this LCA, the inventory due to the separation process is scaled down to the inventory that is needed to only extract the determining co-product. It is assumed that the inventory of the separation process is linearly related to the mass of the extracted material. No potential impacts related to the stockpiling activity itself are considered in this LCA.

For this analysis, the decision tree of a process-oriented LCA is applied. The REEs are separated from each other in different separation steps which take place in different reactors. In this section, it is identified which separation steps are part of the primary production route of REEs, and which separation steps could be considered as “valorization activities” from materials supplied by stockpiles. The order of separation often follows Figure 7C-7 (Lévêque and Maestro 1993; Gupta and Krishnamurthy 2005; Wang et al 2013). If the rare earth concentrate contains mostly light rare earths (LREE), the focus will be put on the left-hand side of the figure, while heavy rare earths (HREE) are mainly extracted in the separation activities on the right-hand side of the figure. However, the exact sequence of separation depends on the composition of the rare earth concentrate. If a separation

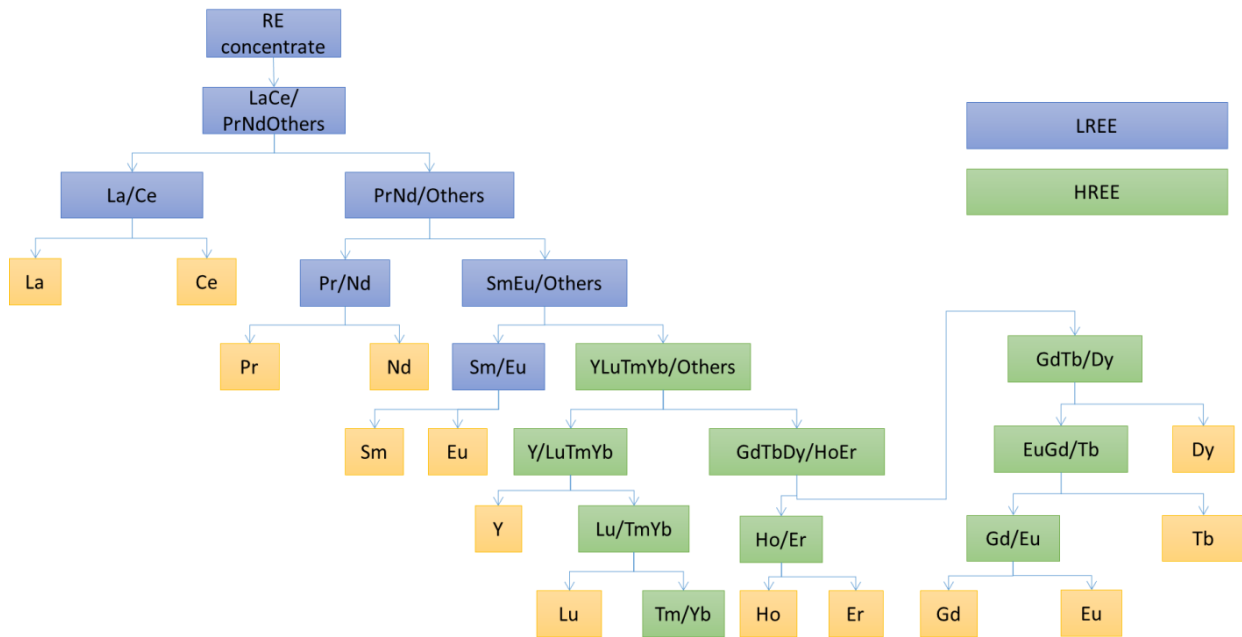


Figure 7C-7 Separation process of REEs (Lévêque and Maestro 1993; Wang et al 2013). The content of the REE mix determines whether the emphasis is put on the LREE or the HREE separation route

activity delivers only REEs of which there is a surplus – for example, lanthanum and cerium – the elements could be stockpiled as unseparated elements.

The increased demand for lanthanum or cerium might be provided from stockpiles, although it would require the separation of LaCe. Whether this separation activity is triggered by the demand for lanthanum or cerium can be identified by the calculation of the determining co-product of this activity. The assumption is done that the revenue of each co-product is sufficient to separate La/Ce. Lanthanum has the highest normalized market trend in the La/Ce mix from Bayan Obo, which is expected to be the largest contributor to the La/Ce stockpiles. This makes lanthanum the determining co-product of this separation activity. The dataset of lanthanum only contains inventory related to the separation of lanthanum and cerium. Similarly, for each separation activity, one determining co-product should be identified.

We will study the effects of an increased demand for yttrium to illustrate the procedure. Before, the Longnan mine in China was identified as the marginal supplier of yttrium. To extract yttrium, the separation steps of “YLuTmYb/Others” and “Y/LuTmYb” will be executed. During this primary production, the dependent co-products “Others” (i.e. “GdTbDyHoEr”) and “LuTmYb” are produced (Figure 7C-7). For these products it should be determined whether they are directly being stockpiled or whether they are valorized, i.e. separated, to be used in other applications. Ideally, the determining co-product of the additional valorization steps is identified, and subsequently, the A-value of this product indicate whether further separation takes place or not. All elements that are contained in the mix of “LuTmYb” have a value of  $A = 0$ , so this mix will directly be stockpiled. In the mix of “Others”, several elements have a value of  $A = 1$ . Due to the lacking knowledge on the exact operation of the separation process, the identification of the determining co-products would be quite uncertain. Therefore, we simply assume that separation takes place for all intermediate flows that contain an element with a value of  $A = 1$ . Separation of GdTbDy/HoEr, GdTb/Dy, EuGd/Tb, Gd/Eu, LaCe/PrNdOthers and PrNd/Others will take place to extract dysprosium, terbium, europium, and neodymium, respectively. The co-products LaCe, praseodymium, samarium, HoEr, and gadolinium will be stockpiled. Dysprosium, terbium, europium and neodymium will be increasingly used in other applications, where they could displace the demand for these materials from other sources. As

dysprosium and neodymium are determining co-products of primary production activities, primary mining can be displaced. However, the displaced demand of terbium and europium from other sources will not displace primary mining – as these elements are not determining co-products – and will lead to an increased use by their marginal users.

To summarize, the effects of an increased demand for yttrium could be the following:

- Increased mining in Longnan, China,
- Separation of YLuTmYb/Others, Y/LuTmYb, GdTbDy/HoEr, GdTb/Dy, EuGd/Tb, Gd/Eu, LaCe/PrNdOthers and PrNd/Others,
- Stockpiling of LuTmYb, LaCe, HoEr, praseodymium, samarium and gadolinium,
- Avoided mining of dysprosium and neodymium (which also avoids the co-production of other elements by these mines!)
- Increased use of europium and terbium by their marginal users.

Note that for LuTmYb, LaCe and HoEr the determining co-product of each separation activity should be identified by the user of any of these elements. The demand for this co-product will cause the burdens of the separation activity, while the dependent co-products could be taken from stockpiles with little additional impacts, similar as praseodymium, samarium, and gadolinium.

*To summarize Sections 3.1.3.1.1. – 3.1.3.1.4, it appears that only neodymium, yttrium and dysprosium are determining co-products from primary production routes. This means that the other REEs – including lanthanum, cerium, terbium and europium – are dependent co-products. It is assumed that the supply of these co-products is fully constrained. The term  $E_v^*$  in Equation E2 can only be used when the supply of the substituted material is unconstrained (see Chapter 6, Section 4.2.3). Therefore, a more detailed analysis is necessary for these REEs. The product-oriented formula (Equation E20 of Section 4.2.3 of Chapter 6) is applied to calculate the effects of a decreased demand for these primary materials.*

#### 3.1.3.2. Is the demand for the dependent co-products constrained?

Table 7C-5 shows that among the REEs that are substituted by the co-products of the recycling process, the demand is constrained for lanthanum and cerium. This means that their marginal suppliers are anthropogenic stocks, hence recycling of these elements results into increased stockpiling. Demand is not constrained for europium and terbium. For these elements, the marginal user must be identified.

#### 3.1.3.3. Identify the marginal user and substitute of europium

In Chapter 6 it was stated that substitutes could be identified on different levels (Habib 2015): detailed composition, component, sub-assembly and conceptual. Europium is mostly used within phosphors for compact fluorescent lamps (CFL), LEDs and video screens (European Commission 2014a). The income elasticity and own-price elasticity of demand for fluorescent lamps are relatively high, which indicates that a fluorescent lamp is a luxury good (Holland et al 2014). From this, we conclude that the user of the fluorescent lamp is the marginal user of europium. In this context, the categorization above is interpreted as follows:

- Detailed composition: the use of europium in YOX
- Component: the use of YOX in fluorescent lamps
- Sub-assembly: the use of phosphors in a lamp
- Conceptual: use of a lamp to provide the function of light

There is no direct substitute for phosphors (ERECON 2014), hence substitution should take place on a conceptual level. LEDs are often identified as good substitutes for the use of europium in CFLs, although they are still more costly than CFLs (ERECON 2014; European Commission 2014a; Guyonnet et al 2014). A decreasing price for europium – due to an increased availability on the market – could increase the price gap between CFLs and LEDs and postpone the transition towards more energy efficient LED lamps. However, CFLs still compete with less energy efficient halogen lamps. A scenario analysis could indicate the relevance of the indirect effects of substituting LED or halogen lamps. If fluorescent lamps are widely displaced by LED lights, there could even be an oversupply of europium (Binnemans 2014; ERECON 2014). In that case, the marginal supplier is, similar as for cerium and lanthanum, supply from stockpiles.

For europium, two potential substitutes are analyzed: halogen lamps or LED lights (European Commission 2014a). The market-price ratio between the fluorescent lamp and the substitutes could indicate whether the products are considered to be good substitutes and whether downstream effects take place, according to Figure 7C-6. LED lamps are more expensive and halogen lamps are cheaper than fluorescent lamps, which gives market-price ratios of  $A_{LED} < 1$  and  $A_{halogen} > 1$ . This suggests that the substitution of halogen lamps leads to positive downstream effects, while the substitution of LED lamps leads to negative downstream effects. The difference in the energy efficiency of the lamps obviously leads to differences in electricity consumption during the use phase. Furthermore, a halogen lamp needs to be replaced more often than a CFL, which has a shorter lifetime than LED lamps (Navigant Consulting Inc. 2012; Holland et al 2014). The number of replacements and the price of the substituted or increased electricity consumption are included in the calculation of the market-price ratio:

$$E3. \quad A_{LED} = \frac{\text{Fluorescent lamp} + 2 * \text{Fluorescent lamp} + \Delta_{\text{electricity}}}{LED \text{ lamp}}$$

And

$$E4. \quad A_{halogen} = \frac{\text{Fluorescent lamp}}{\text{Halogen lamp} + 9 * \text{Halogen lamp} + \Delta_{\text{electricity}}}$$

Interestingly, this results in market-price ratios of  $A_{LED} > 1$  and  $A_{halogen} < 1$  (Holland et al 2014). This suggests that the halogen lamp has additional benefits over the fluorescent lamp that were not yet identified, and that the LED lamp has additional drawbacks. It is known that halogen lamps are sometimes preferred over energy-saving lamps due to their warm light and stability issues related to energy-saving lamps (Holland et al 2014). Considering different market segments, this suggests that fluorescent lamps could substitute halogen lamps in market segments with lower quality demands for the lamp. A cheaper type of halogen lamp could be identified as a better substitute. Similarly, fluorescent lamps might be considered good substitutes for LED lamps in higher market segments with higher quality demands. However, this theory does not seem justified in this application, due to the fact that the fluorescent lamp was earlier identified as a luxury good. This rebuts the indication that fluorescent lamps only compete with halogen lamps in lower market segments. Holland et al. (2014) suggest that investment costs – related to the high purchase price of energy-saving lamps – often act as a barrier to adoption. Consumers can make irrational decisions regarding products that provide a financial benefit in the long run. LaBlanc showed that consumers discount future benefits in a hyperbolic manner rather than exponentially, which is generally assumed (LaBlanc 2014). This can be integrated into Equations E3 and E4 by discounting the costs of the avoided or increased electricity consumption and the number of replacements. This might result in a value of  $A$  more close to 1. The considerations with regard to the marginal supplier of europium are summarized in Figure 7C-8.

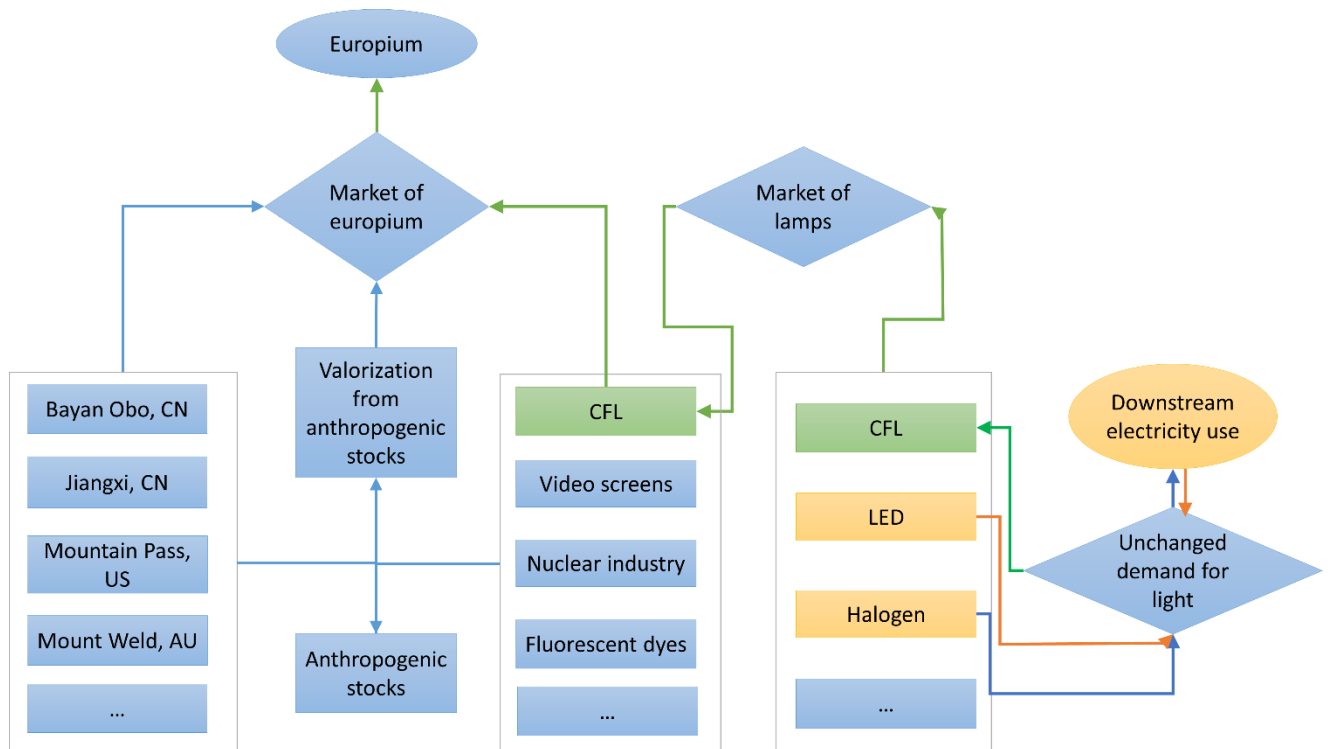


Figure 7C-8 Identification of the affected process due to an increased demand for europium. Supply from primary production routes is constrained, due to the fact that europium is not a determining co-product of a mining activity. There are no stockpiles of europium (foreseen in the near future). Therefore, demand is not constrained and the additional demand does not lead to the additional valorization of stockpiles. Instead, the marginal user is affected. The marginal user is the fluorescent lamp (CFL). Europium cannot be substituted on an elemental level, neither can YOX. However, a fluorescent lamp can be replaced by a LED lamp or a halogen lamp. This substitution leads to downstream effects: an increased or decreased use of electricity during the use phase. In short: the additional demand for europium leads to a decreased production of fluorescent lamps and an increased use of LED or halogen lamps, and subsequently, a decreased or increased use of electricity, respectively.

#### Identify downstream effects due to the substitution of europium

Only the downstream effects that lead to different costs for the marginal user are included in the calculation of the market-price ratio. However, all downstream effects that are caused by the substitution must be modeled in the inventory of the LCA. Several LCA studies on the comparison between these three types of lamps (fluorescent, LED and halogen) have indicated that electricity consumption during the use phase is the largest contributor to impacts of all of these lamps (Navigant Consulting Inc. 2012; Principi and Fioretti 2014). These LCA studies do not all show a similar level of detail for the inventory of the manufacturing and end-of-life stage. For example, some inventories take the consumption of LAP and YOX into consideration (e.g. (Tan et al 2015)), while this is excluded in other inventories (e.g. (Principi and Fioretti 2014)). Therefore, inventory values for manufacturing are difficult to compare between the different LCA studies. Inventory related to the use phase of a halogen lamp, fluorescent lamp and LED lamp are taken from (Navigant Consulting Inc. 2012). The report uses 20 million lumen-hours as the functional unit, which corresponds to 26.7 halogen lamps, 2.6 fluorescent lamps, and 1 LED lamp. The increased availability of 1 kg of europium could lead to an increased production of 17.000 fluorescent lamps, where we assume a full elasticity of demand. This increased production of fluorescent lamps could lead to either a decreased production of 174.000 halogen lamps or a decreased production of 6.500 LED lamps. It should be noted that the inventory that is used for the lamp from Tan et al. (2015) might not correspond to the electricity consumption of the fluorescent lamp that was taken as a reference in (Navigant Consulting Inc. 2012). It is not exactly

known what lamp would be used as a substitute for the fluorescent lamp if more or less europium becomes available. Therefore, four scenarios are investigated:

- *Fluorescent lamps are only competing with LED lamps:* Europium is mainly used for fluorescent lamps. As long as we are still using fluorescent lamps, LED lamps do not become competitive and will not gain a larger market share. However, LED lamps are more efficient than fluorescent lamps. Therefore, the production of fluorescent lamps should not be further sustained and focus should be put on the more efficient LED lamps.
- *Fluorescent lamps are for 50% competing with LED lamps, and for 50% with halogen lamps*
- *Fluorescent lamps are only competing with halogen lamps:* Fluorescent lamps are needed in the transition to sustainable lighting. Fluorescent lamps are necessary to displace halogen lamps, that are much more energy-consuming. Therefore, the availability of materials needed for fluorescent lamps should be safeguarded. This could lead to a reduction of energy consumption during the use phase of a lamp.
- *Fluorescent lamps are becoming superfluous, and europium is supplied from stockpiles:* Fluorescent lamps will be displaced by LED lights. LED lamps use much fewer phosphors than fluorescent lamps. With the current production quantities of europium, there will be a surplus of this material when fluorescent lamps become less popular. As long as there are no alternative applications for europium, there will be a surplus of this material in the (near) future when LED lights have displaced most fluorescent lamps.

These scenarios represent different market situations of the fluorescent lamp, as well as its competitors. The only difference that is considered between these marginal suppliers is their downstream electricity consumption: LED lights are more efficient and halogen lamps use more electricity than fluorescent lamps. If europium is supplied from stockpiles, no additional downstream effects are considered. The electricity consumption is represented by the French or the Swiss electricity mix. The Swiss mix is used for comparison, due to the fact that the model of this mix in ecoinvent causes low environmental impacts compared to the electricity mix of other countries. In this way, the effect could be estimated for greener electricity mixes of the future, and the contribution of the effect is minimized to enable to distinguish other effects as well.

#### 3.1.3.4. Identify the marginal user and substitute of terbium

Terbium is also mainly used within phosphors, so the same reflection as for europium could be relevant (European Commission 2014a). Terbium is also used in permanent magnets, where it can displace dysprosium and vice versa (Binnemans 2014). In that case, the additional supply of terbium might displace the primary mining of dysprosium. The market-price ratio between terbium and dysprosium gives  $A > 1$ . This might indicate that 1 kg of terbium could displace more than 1 kg of dysprosium, or there are additional downstream benefits due to the use of terbium instead of dysprosium. It could also indicate that terbium can be used in more valuable markets than permanent magnets. This is also suggested by Binnemans (2014), who states that dysprosium is not often displaced by terbium, due to the important application of terbium in phosphors. In that case, the indirect effects due to the additional supply or demand of terbium are the same as of europium. However, Binnemans also states that the application of terbium in magnets may become more relevant when fluorescent lamps will be more and more displaced by LED lights (Binnemans 2014). The European Commission (2014) is not conclusive about the current market situation of terbium. Binnemans (2014) mentions that terbium can, at the time of his writing, be supplied from stockpiles. Therefore, also for the marginal user of terbium, multiple scenarios are possible. Fluorescent lamps could be considered as the marginal user. When fluorescent lamps are becoming superfluous due to the implementation of LED lights, terbium

could substitute dysprosium or be supplied from stockpiles. To simplify the case study, it is assumed that terbium displaces dysprosium in a 1:1 mass ratio and no downstream effects take place.

### 3.1.4. Extended mathematical approach to calculating the consequences of the production of recycled YOX

From the findings in Section 3.1.3, it appeared that Equation E2 was not sufficiently detailed to calculate the consequences of the recycling of YOX. The parameter  $E_v^*$  is replaced in Equation E5 by a term that calculates the decreased demand for a product for which supply is (partly) constrained. This term – represented in purple – was presented in the product-oriented Equation E20 of Chapter 6. The values for the additional parameters in Equation E5 are given in Table 7C-7.

$$\begin{aligned}
 \text{E5. } E_{tot} = & \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{(1 - A_{RC_i})}{C_{RC_i}} * (E_{RC_{YOX}} - \right. \\
 & E_{d_{powder}}^*) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \left. \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \sum_{i=1}^n RI_i * \\
 & RRE_i * \left( (1 - A_{RRE_i}) * E_{d_i} + A_{RRE_i} * \left( E_{RRE_i} + C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * \left( \Delta E_{\alpha_i} - \left( \sum_{i=1}^n S_i * E_{v_i} + \right. \right. \right. \right. \\
 & \left. \left. \left. \sum_{i=1}^n (1 - S_i) * \left( (1 - A_{RC_i}) * \left( E_{CR_i} - \frac{E_{d_i}^*}{C_i} \right) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \right) \right) \right) \right) \right) + \\
 & \sum_{i=1}^n RI_i * RRE_i * \left( E_{RRE_{1i}} - A_{RRE_i} * C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * E_{v_i}^* \right)
 \end{aligned}$$

Table 7C-6 Legend of the terms in purple for Equation E5. In a product-oriented approach, “recycled” refers to a material with constrained supply, and “primary” to a material with unconstrained supply. The legend of the other terms in this equation is given in Table 7C-2

Term	Explanation	Value
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{CR}$	LCI due to the valorization process related to the consumed material (including LCI of material losses during the valorization process), per unit of the determining co-product of the valorization process	LCI / unit of valorized product
$S$	Rate of supply constraints. If supply is fully elastic, $S = 1$ . If supply is fully inelastic, $S = 0$	$0 \leq \dots \leq 1$
$C$	Conversion efficiency of the valorization process related to the consumed product	Unit of useful output / unit of input material
$Q_{RC}/Q_v$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material

Term	Explanation	Value
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})}{(P_v + \sum_{i=1}^n Q_{\Delta i} * P_{\Delta i})} * (Q_{RC}/Q_v)^{-1}$
$E_{\alpha}$	LCI due to the downstream impacts related to the use of the material in the functional unit	$E_{\alpha_v} + \Delta E_{\alpha}$
$E_{\alpha_v}$	LCI due to the downstream impacts if only primary material were used	LCI / unit of analysis
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material	LCI / unit of displaced primary material

Table 7C-7 Summary of values for the parameters of Equation E5

	Glass	La/Ce (Det. Co-product Ce)	La	Tb	Eu
$S$	1	0	0	0	0
$E_v^*$	glass tube, borosilicate				
$A_{RC}$		0	0	1	1
$E_{CR}$		0	Separation La/Ce		
$E_d^*/C$		Stockpiling	Stockpiling		
$Q_{RC}/Q_v$				1	1
$E_v$				LCI Dysprosium	LCI Halogen or LED lamp
$\Delta E_{\alpha}$				(LCI <sub>downstream</sub> Tb – LCI <sub>downstream</sub> Dy) / unit of displaced dysprosium	(LCI <sub>downstream</sub> CFL – LCI <sub>downstream</sub> alternative lamp) / unit of displaced halogen or LED lamp



### 3.2. Product-oriented LCA

#### 3.2.1. Demand for recycled YOX

In the product-oriented LCA, the functional unit is “the demand for 1 kg of recycled YOX”. The system boundaries of the goal and scope definition in Chapter 7A are repeated in Figure 7C-9, with a more detailed description of the background sub-system. In the product-oriented LCA, it is assessed which material flow is likely to be affected by the increased demand for recycled YOX. The effects of this demand are assessed by the steps of Figure 7C-3. Supply is constrained due to the fact that we analyze a recycled product: the availability of phosphorous powder is limited by the availability of used fluorescent lamps. Now, it should be determined whether demand constraints exist. For this, the market-price ratio between the recycled YOX and primary YOX is calculated, which is  $A = 0.9$  (Lartigue-Peyrou 2016), i.e. supply constraints are more dominant than demand constraints. This means that 10% of the demanded YOX leads to increased recycling and avoided waste treatment of the powder, and 90% leads to a reduced supply to the “market of materials” which is supplemented by an increased production of primary YOX (Figure 7C-10). The supply of primary YOX is in principle not constrained. In fact, in this case study, it is assumed that the supply of primary YOX is fully elastic. However, during the primary production, several materials are required of which supply is not fully elastic, such as europium. The increased demand for these products can be subsequently modeled with the CLD.

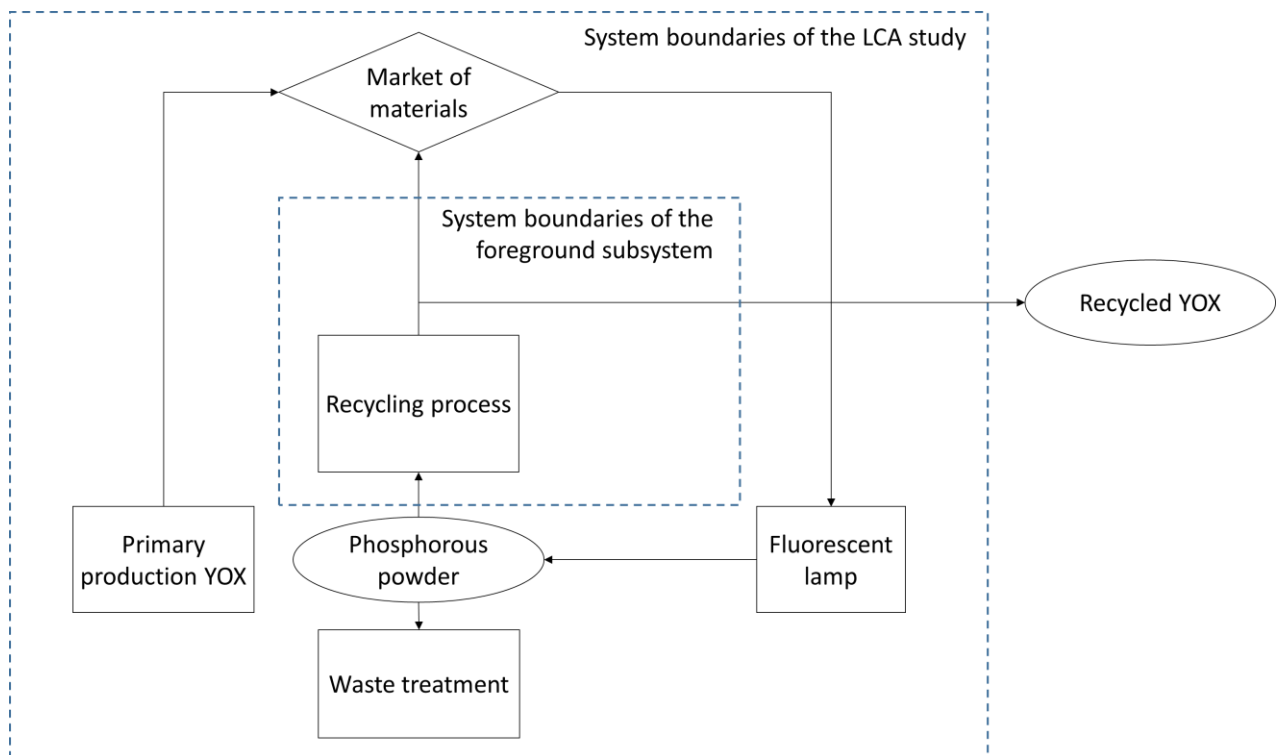


Figure 7C-9 Cradle-to-gate system boundaries of the product-oriented LCA with the functional unit of 1 kg of recycled YOX



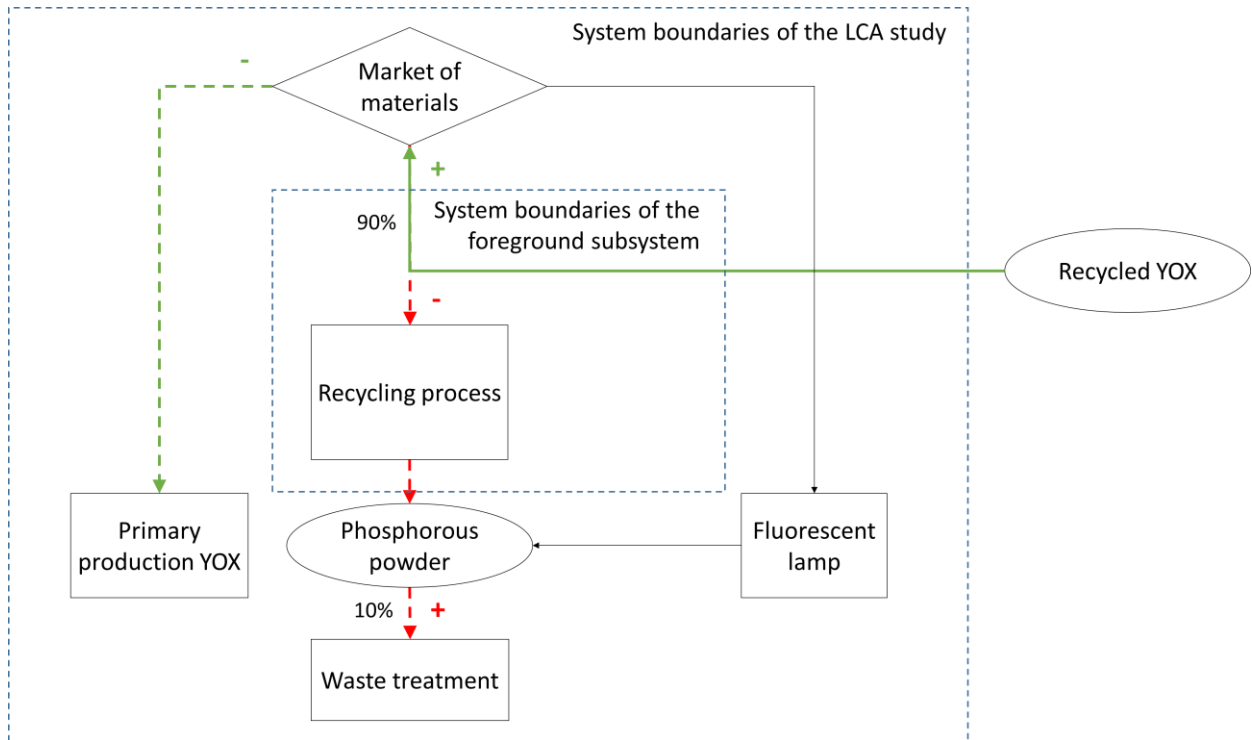


Figure 7C-11 Identification of the affected processes due to an increased supply of recycled YOX with a value of  $A = 0.9$ . The dashed arrows are affected

### 3.2.3. Mathematical approach to calculating the consequences of the demand of 1 lamp

The inventory of the demand for 1 kg of YOX or 1 fluorescent lamp can be calculated by the equations of Chapter 6. Equation E1 is used again and this time all terms of the equation are relevant. The green terms of Equation E6 represent the parameters that refer to the additional demand of recycled YOX. The blue terms refer to the additional supply of phosphorous powder at the end of life of the fluorescent lamp. Note that – if the recycling process of the powder is modeled – the consequences of the co-production of glass, cerium, lanthanum, terbium and europium must be modeled as well, as demonstrated in Section 3.1. The values for the parameters of Equation E6 are summarized in Table 7C-8.

$$\begin{aligned}
 \text{E6. } E_{tot} = & \sum_{i=1}^n Q_i * E_{\alpha_i} + \sum_{i=1}^n Q_i * (1 - RC_i) * E_{v_i} + \sum_{i=1}^n Q_i * RC_i * \left( \frac{(1 - A_{RC_i})}{C_{RC_i}} * \right. \\
 & \left. (E_{RC_{YOX}} - E_{d_{powder}}^*) + A_{RC_i} * \frac{Q_{RC_i}}{Q_{v_i}} * (E_{v_i} - \Delta E_{\alpha_i}) \right) + \sum_{i=1}^n RI_i * (1 - RRE_i) * E_{d_i} + \\
 & \sum_{i=1}^n RI_i * RRE_i * \left( (1 - A_{RRE_i}) * E_{d_i} + A_{RRE_i} * \left( E_{RRE_i} + C_{RRE_i} * \frac{Q_{RRE_i}}{Q_{v_i}^*} * (\Delta E_{\alpha_i}^* - E_{v_i}^*) \right) \right)
 \end{aligned}$$

Table 7C-8 Summary of values for the parameters of Equation E6

	YOX (F.U. 1 kg YOX)	YOX (F.U. 1 lamp)	Phosphorous powder (F.U. 1 lamp)
Q	1 kg	8.3E-4 kg	
$E_{\alpha}$	0 (cradle-to-gate)	LCI related to the downstream use of YOX	
RC	1	0 – 1*	
$A_{RC}$	0.9	0.9	
$C_{RC}$	1 kg YOX / 9.92 kg powder	1 kg YOX / 9.92 kg powder	
$E_{RCYOX}$	LCI/kg powder	LCI/kg powder	
$E_{d,powder}^*$	LCI/kg powder	LCI/kg powder	
$Q_{RC}/Q_v$	1	1	
$E_v$	Primary YOX	Primary YOX	
$\Delta E_{\alpha}$	0	0	
RI			2E-3 kg
RRE			0 – 1*
$E_d$			LCI/kg powder
$A_{RRE}$			0.9
$E_{RRE}$			LCI/kg powder
$C_{RRE}$			1 kg YOX / 9.92 kg powder
$Q_{RRE}/Q_v^*$			1
$\Delta E_{\alpha}^*$			0
$E_v^*$			Primary YOX

\*Closed-loop recycling takes place when RC = 0.24 and RRE = 1

#### 4. Impact assessment and interpretation

The impact assessment is done in Simapro 8.2.3.0 with the impact assessment method ILCD Midpoint 2011 v 1.05.

##### 4.1. Process-oriented LCA

First, the results of the process-oriented LCAs are presented, where the focus was on the valorization process of the phosphorous powder into recycled YOX.

##### 4.1.1. Quantifying environmental impacts

*What environmental impacts are caused by the production of 1 kg of recycled YOX from phosphorous powder?*

During the recycling process, an excess of europium is produced that is not directly used to produce YOX. In the inventory analysis, it appeared that the marginal supplier of europium is its marginal user. The impact assessment is done for the four scenarios for the marginal user of europium, as described in Section 3.1.3.3.1. The marginal user was identified to be the user of a fluorescent lamp, which could compete with LED lamps, halogen lamps or a mix of both. If LED lamps gain more market share, fluorescent lamps could become superfluous. In that case, europium might be supplied from stockpiles. Table 7C-9 shows the impact results for these scenarios in which the French electricity mix is used to represent the electricity use of the lamps.

Table 7C-9 Environmental impacts caused by the recycling of 1 kg of YOX. Different marginal suppliers of europium are considered, and the French electricity mix is used to represent downstream electricity use by the lamps. Negative values represent avoided impacts – i.e. environmental benefits

Impact category	Unit	100% LED	50% LED, 50% halogen	100% halogen	Stockpiling
Climate change	kg CO <sub>2</sub> eq	1E+02	-8E+02	-2E+03	5E+01
Ozone depletion	kg CFC-11 eq	8E-05	-1E-03	-2E-03	1E-05
Human toxicity, non-cancer effects	CTUh	5E-05	-5E-04	-1E-03	2E-05
Human toxicity, cancer effects	CTUh	5E-06	-6E-05	-1E-04	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	6E-02	-5E-01	-1E+00	3E-02
Ionizing radiation HH	kBq U235 eq	4E+02	-8E+03	-2E+04	3E+01
Ionizing radiation E (interim)	CTUe	8E-04	-1E-02	-3E-02	6E-05
Photochemical ozone formation	kg NMVOC eq	2E-01	-2E+00	-4E+00	1E-01
Acidification	molc H <sup>+</sup> eq	1E+00	-5E+00	-1E+01	2E-01
Terrestrial eutrophication	molc N eq	1E+00	-7E+00	-1E+01	4E-01
Freshwater eutrophication	kg P eq	3E-02	0E+00	-1E+00	1E-02
Marine eutrophication	kg N eq	-3E-01	-2E+00	-3E+00	-4E-01
Freshwater ecotoxicity	CTUe	2E+03	-2E+04	-5E+04	4E+02
Land use	kg C deficit	1E+02	-6E+02	-1E+03	8E+01
Water resource depletion	m <sup>3</sup> water eq	1E+00	-8E+00	-2E+01	1E+00
Mineral, fossil & ren resource depletion	kg Sb eq	5E-03	-6E-02	-1E-01	1E-03

The valorization of YOX leads to additional environmental impacts when fluorescent lamps compete with LED lamps. Due to the increased availability of the co-produced europium, more fluorescent lamps can be produced to the expense of LED lamps. As LED lamps consume less electricity in their lifetime, the co-production of europium results into a higher downstream electricity consumption.

However, the valorization of the powder leads to environmental benefits as long as the fluorescent lamps still compete with halogen lamps. This is represented by a negative value of the impact results – i.e. impacts are avoided. The additional production of europium could result in an increased production of fluorescent lamps and a reduced production of halogen lamps. This leads to a decreased use of electricity downstream. An additional analysis is done using the Swiss electricity mix to represent the energy use of the lamps (Table 7C-10). The French electricity mix is more impactful than the Swiss mix, which makes the effects related to the co-production of europium more pronounced when the French mix is used to represent downstream electricity use. For further analysis, the Swiss mix is used to reduce the contribution of this downstream effect to the overall impacts of the products and processes.

Table 7C-10 Environmental impacts caused by the recycling of 1 kg of YOX. Different marginal suppliers of europium are considered, and the Swiss electricity mix is used to represent downstream electricity use by the lamps.

Impact category	Unit	100% LED	50% LED, 50% halogen	100% halogen	Stockpiling
Climate change	kg CO <sub>2</sub> eq	6E+01	-9E+01	-2E+02	5E+01
Ozone depletion	kg CFC-11 eq	1E-05	4E-06	-3E-06	1E-05
Human toxicity, non-cancer effects	CTUh	3E-05	-1E-04	-2E-04	2E-05
Human toxicity, cancer effects	CTUh	3E-06	-3E-05	-6E-05	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	4E-02	-9E-02	-2E-01	3E-02
Ionizing radiation HH	kBq U235 eq	3E+01	3E+01	3E+01	3E+01
Ionizing radiation E (interim)	CTUe	6E-05	5E-05	3E-05	6E-05
Photochemical ozone formation	kg NMVOC eq	1E-01	-3E-01	-1E+00	1E-01
Acidification	molc H <sup>+</sup> eq	3E-01	-4E-01	-1E+00	2E-01
Terrestrial eutrophication	molc N eq	5E-01	-1E+00	-2E+00	4E-01
Freshwater eutrophication	kg P eq	2E-02	-8E-02	-2E-01	1E-02
Marine eutrophication	kg N eq	-4E-01	-5E-01	-1E+00	-4E-01
Freshwater ecotoxicity	CTUe	2E+03	-2E+04	-4E+04	4E+02
Land use	kg C deficit	8E+01	5E+01	2E+01	8E+01
Water resource depletion	m <sup>3</sup> water eq	1E+00	-7E+00	-2E+01	1E+00
Mineral, fossil & ren resource depletion	kg Sb eq	1E-03	2E-03	3E-03	1E-03

In the scenario where europium can be supplied from stockpiles, the additional recycling of YOX causes impacts regarding most impact categories, although it has a beneficial effect on marine eutrophication and mineral, fossil and resource depletion due to the co-production of terbium, which leads to avoided mining of dysprosium. Although this scenario leads to additional impacts, the environmental impacts of the recycling process are still lower than in the scenario where the marginal user of europium is the fluorescent lamp, which only competes with LED lamps.

The results of this chapter are expressed as potential impacts per kilogram of recycled YOX. This is a production-oriented perspective, as described in Chapter 6. This value can also be expressed in terms of *treatment of phosphorous powder*. This can be achieved by dividing the potential impacts by the conversion rate of phosphorous powder into recycled YOX (i.e. 1 kg of YOX/9.92 kg of powder).

It should be noted that the calculated impacts are not all valid at the same time; the answers are not equally true in one context. In fact, this analysis has shown that a good understanding of the market is required to obtain robust results in the LCA study. It depends for example to what extent LED lamps are relevant in the lighting market, and in which country the consumption of lamps is expected to be affected. This type of analysis was outside the scope of this study, which mainly aimed to demonstrate a modeling methodology in consequential LCA. However, this understanding of the market situation is not only required in a consequential LCA. The economic viability of the recycling route is also dependent on the (foreseen) market situation.

*What environmental impacts are caused by the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029*

*kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps?*

Due to the fact that indirect effects of the co-production of, among others, europium have a large influence on the results, it is interesting to see what impacts are caused by the processes within the foreground system. Therefore, the additional functions provided by the treatment of waste and the supply of co-products are added to the functional unit (i.e. system expansion). The results of this analysis are given in Table 7C-11.

Table 7C-11 Environmental impacts caused by the production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps (system expansion).

Impact category	Unit	Total
Climate change	kg CO <sub>2</sub> eq	6E+01
Ozone depletion	kg CFC-11 eq	1E-05
Human toxicity, non-cancer effects	CTUh	2E-05
Human toxicity, cancer effects	CTUh	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	4E-02
Ionizing radiation HH	kBq U235 eq	3E+01
Ionizing radiation E (interim)	CTUe	6E-05
Photochemical ozone formation	kg NMVOC eq	1E-01
Acidification	molc H <sup>+</sup> eq	3E-01
Terrestrial eutrophication	molc N eq	5E-01
Freshwater eutrophication	kg P eq	2E-02
Marine eutrophication	kg N eq	4E-02
Freshwater ecotoxicity	CTUe	5E+02
Land use	kg C deficit	9E+01
Water resource depletion	m <sup>3</sup> water eq	1E+00
Mineral, fossil & ren resource depletion	kg Sb eq	2E-03

#### 4.1.2. Identifying options for improvement

*How can we reduce the environmental impacts of the production of 1 kg of recycled YOX from phosphorous powder, in order to reduce global impacts?*

From the results in Table 7C-9 and Table 7C-10 it already appeared that the marginal user of europium has a large influence on the results. As long as fluorescent lamps displace halogen lamps, efforts to increase the production rate of europium could lead to environmental benefits. The following analysis is done under the assumption that europium is supplied by stockpiles, to eliminate the indirect effects of this material. Improvement options could be sought for to decrease the impact of the treatment of the phosphorous powder, which is the largest contributor to the impacts of the recycling process (Figure 7C-12). The valorization of terbium – which is modeled as avoided mining of dysprosium – and lanthanum, and the avoided waste treatment of the powder are the largest contributors to the environmental benefits of the recycling process. Increasing the recycling efficiency of these elements could lead to lower impacts.

As an additional analysis, only processes that can directly be influenced by the company are considered here. From Figure 7C-12 it already appeared that the largest contributor among these processes is the treatment of the phosphorous powder.

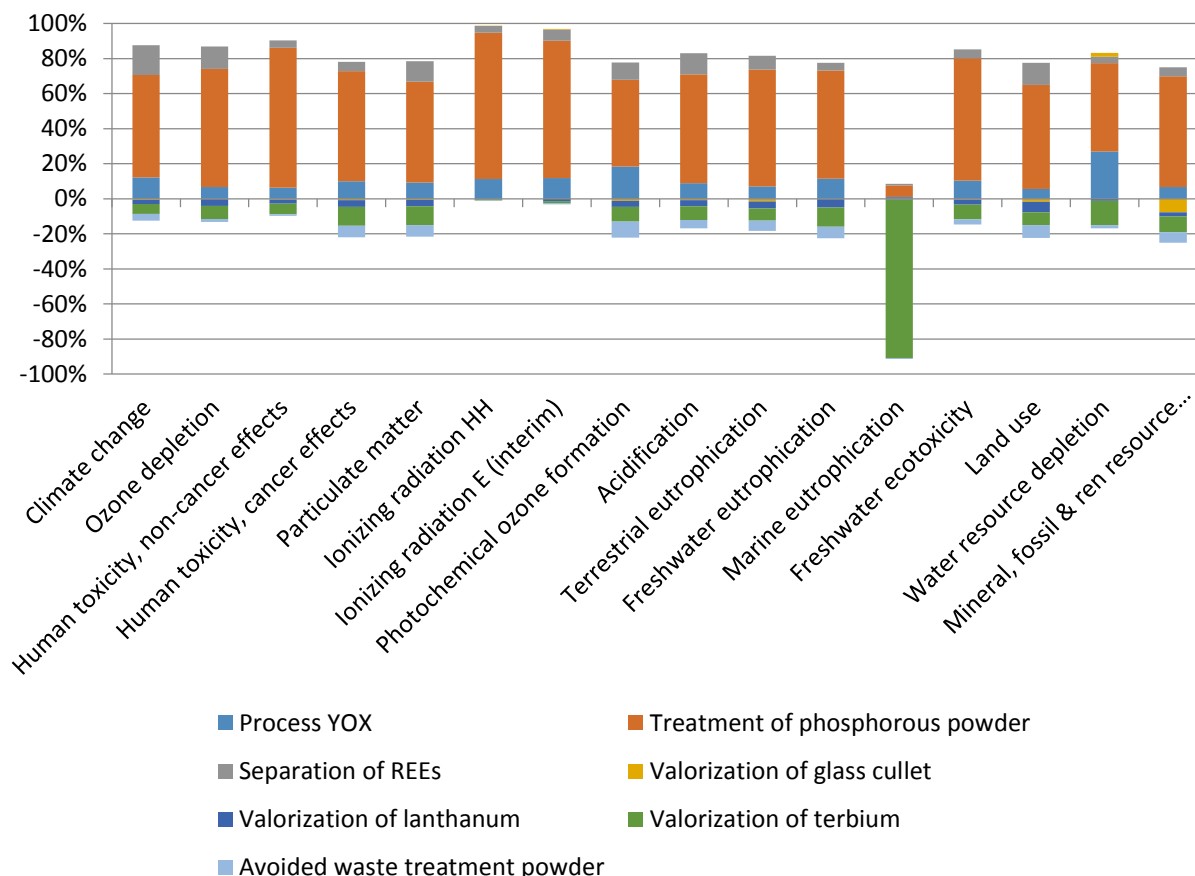


Figure 7C-12 Contribution analysis of the impacts caused by the recycling process of 1 kg of YOX (europium is supplied from stockpiles)

#### 4.1.3. Decision-making

*Does the production of 1 kg of recycled YOX from phosphorous powder have lower consequences on global impacts than the production of primary YOX?*

To compare the recycling process with the primary production process of YOX, again the four scenarios for the marginal supplier of europium as described above were investigated. The results of these scenarios for the primary production of YOX are given in Table 7C-12. Also here, the choice of the marginal supplier of europium has a large influence on the impacts of the primary production of YOX. This is due to the fact that primary europium is used to make YOX. The increased demand for primary YOX leads to a decreased availability of europium elsewhere, and subsequently to an increased production of LED lamps or halogen lamps, with their corresponding downstream impacts. For these downstream impacts, the Swiss electricity mix is used. Therefore, these results can be compared to the results in Table 7C-10. Note that this analysis does not imply that the YOX of the functional unit is used in a fluorescent lamp. Even if this YOX is used in fluorescent dyes (see Figure 7C-8), the downstream effects of the alternative lamp are modeled, as the fluorescent lamp is the marginal user.

When fluorescent lamps compete with LED lamps, the production of primary YOX is environmentally beneficial. This could be interpreted as follows: the production of primary YOX reduces the availability of europium on the market and increases its price. This reduces the possibility for other companies to produce fluorescent lights and stimulates the production of more LED lights. Therefore, the demand for YOX avoids the electricity need related to fluorescent lights and leads to the production of electricity related to the use of LED lights. If YOX is used in the fluorescent lamp and electricity is



modeled in the use phase (which is not included in the current cradle-to-gate study), this electricity need is canceled out by the indirect effects of the use of europium. The electricity need is subsequently indirectly represented by the electricity need of LED lamps. As LED lights are more efficient, the cradle-to-gate study shows an effect that is beneficial for the environment.

Table 7C-12 Environmental impacts caused by the primary production of 1 kg of YOX, where the marginal supplier of europium is either the fluorescent lamp, which competes with LED lamps, halogen lamps or stockpiles.

Impact category	Unit	100% LED	50% LED, 50% halogen	100% halogen	Stockpiling
Climate change	kg CO <sub>2</sub> eq	-5E+01	2E+03	4E+03	5E+01
Ozone depletion	kg CFC-11 eq	4E-06	1E-04	2E-04	9E-06
Human toxicity, non-cancer effects	CTUh	-8E-05	2E-03	3E-03	1E-05
Human toxicity, cancer effects	CTUh	-2E-05	4E-04	8E-04	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	-3E-02	2E+00	3E+00	5E-02
Ionizing radiation HH	kBq U235 eq	-2E-01	5E+01	1E+02	2E+00
Ionizing radiation E (interim)	CTUe	-2E-06	2E-04	5E-04	1E-05
Photochemical ozone formation	kg NMVOC eq	-2E-01	6E+00	1E+01	1E-01
Acidification	molc H <sup>+</sup> eq	-2E-01	9E+00	2E+01	3E-01
Terrestrial eutrophication	molc N eq	-4E-01	2E+01	4E+01	5E-01
Freshwater eutrophication	kg P eq	-4E-02	1E+00	2E+00	2E-02
Marine eutrophication	kg N eq	3E+00	5E+00	6E+00	3E+00
Freshwater ecotoxicity	CTUe	-1E+04	3E+05	6E+05	4E+02
Land use	kg C deficit	6E+01	4E+02	8E+02	8E+01
Water resource depletion	m <sup>3</sup> water eq	-4E+00	1E+02	2E+02	1E+00
Mineral, fossil & ren resource depletion	kg Sb eq	3E-01	3E-01	3E-01	3E-01

Figure 7C-13 to Figure 7C-16 show the results of the comparison between the recycling and the primary production of recycled YOX for the four scenarios. When fluorescent lamps only compete with LED lamps, the production of primary YOX causes lower impacts than the recycling of YOX for almost all impact categories, except for marine eutrophication and mineral, fossil and renewable resource depletion (Figure 7C-13). These impact categories represent the use of the mining site.

When fluorescent lamps compete with halogen lamps (Figure 7C-14 and Figure 7C-15), the recycling process causes lower impacts – and often even leads to environmental benefits – compared to the primary production process. When europium is supplied from stockpiles (Figure 7C-16), the recycling route causes higher impacts than the primary production route with regard to climate change, ozone layer depletion, human toxicity (non-cancer effects) and ionizing radiation.

The market situation of the lamps appears to be very relevant in the calculation of the impacts of the recycling process. Therefore, a sensitivity analysis to determine the moment when the recycling process is environmentally beneficial is presented in Annex III. This analysis shows that the recycling of YOX is environmentally preferable over the primary production of YOX if the contribution of LED lamps in the mix of substitutes for fluorescent lamps is below 90%. The recycling process becomes

even environmentally beneficial (i.e. causing negative impacts) regarding most impact categories when the contribution of LED is below 80%.

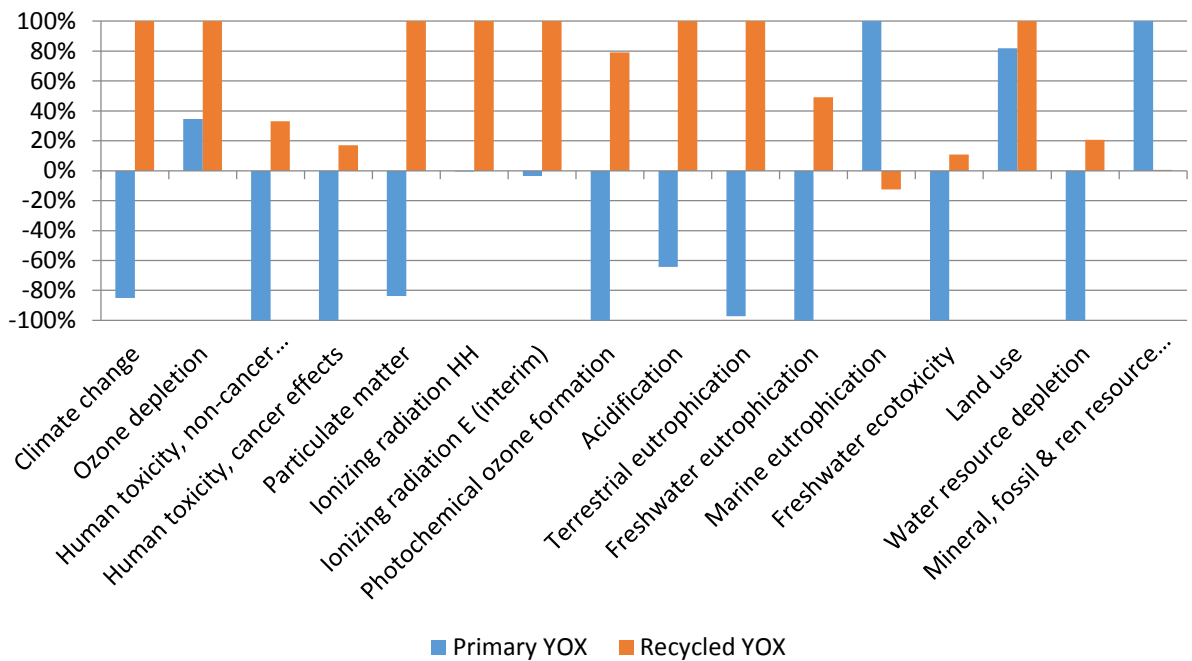


Figure 7C-13 Comparison of the impacts caused by the primary production route and the recycling route of YOX. In this scenario, the marginal supplier of europium is its marginal user – i.e. the fluorescent lamp, which can be substituted by LED lamps

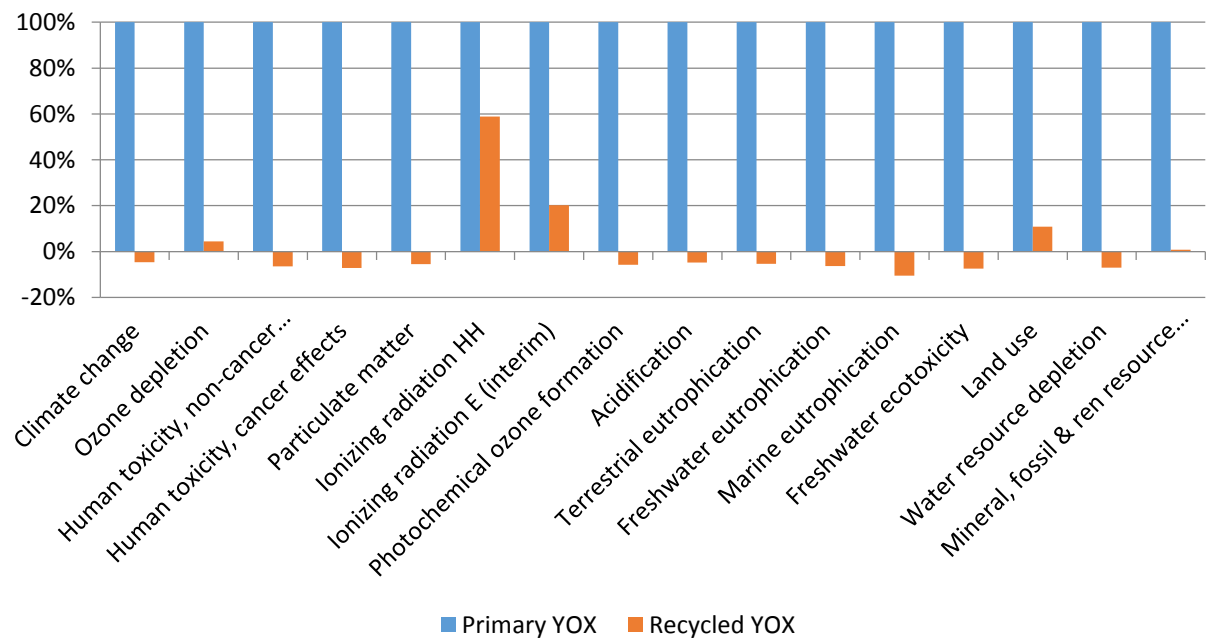


Figure 7C-14 Comparison of the impacts caused by the primary production route and the recycling route of YOX. In this scenario, the marginal supplier of europium is its marginal user – i.e. the fluorescent lamp, which can be substituted by a mix of LED lamps and halogen lamps

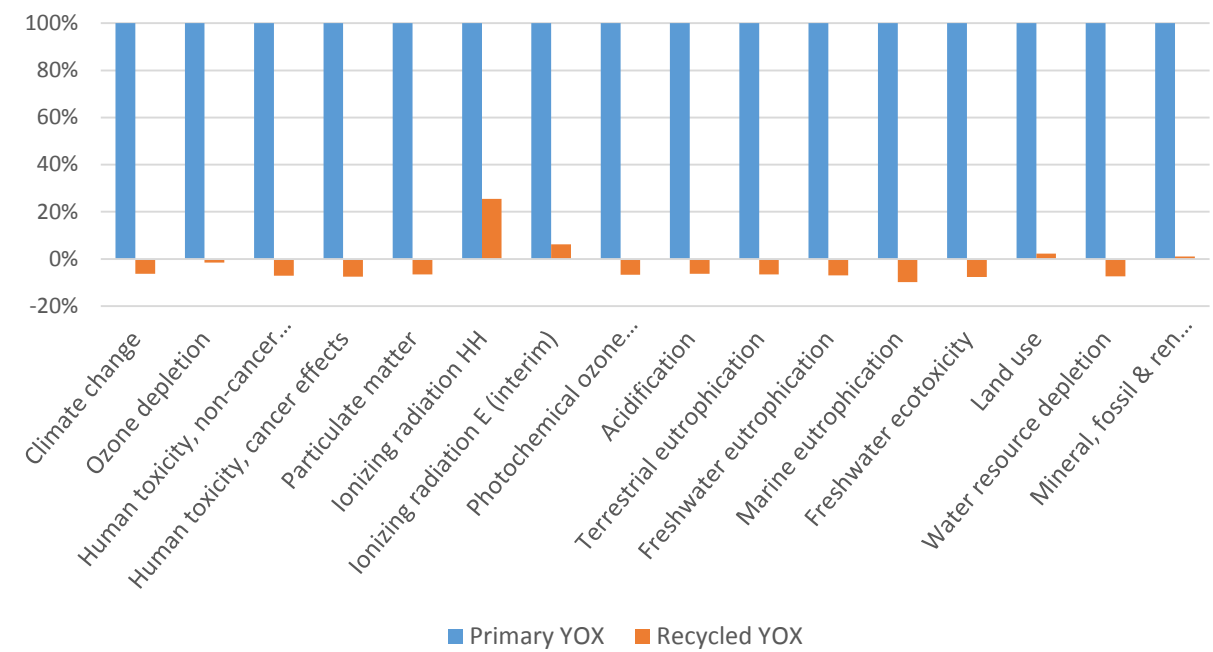


Figure 7C-15 Comparison of the impacts caused by the primary production route and the recycling route of YOX. In this scenario, the marginal supplier of europium is its marginal user – i.e. the fluorescent lamp, which can be substituted by halogen lamps

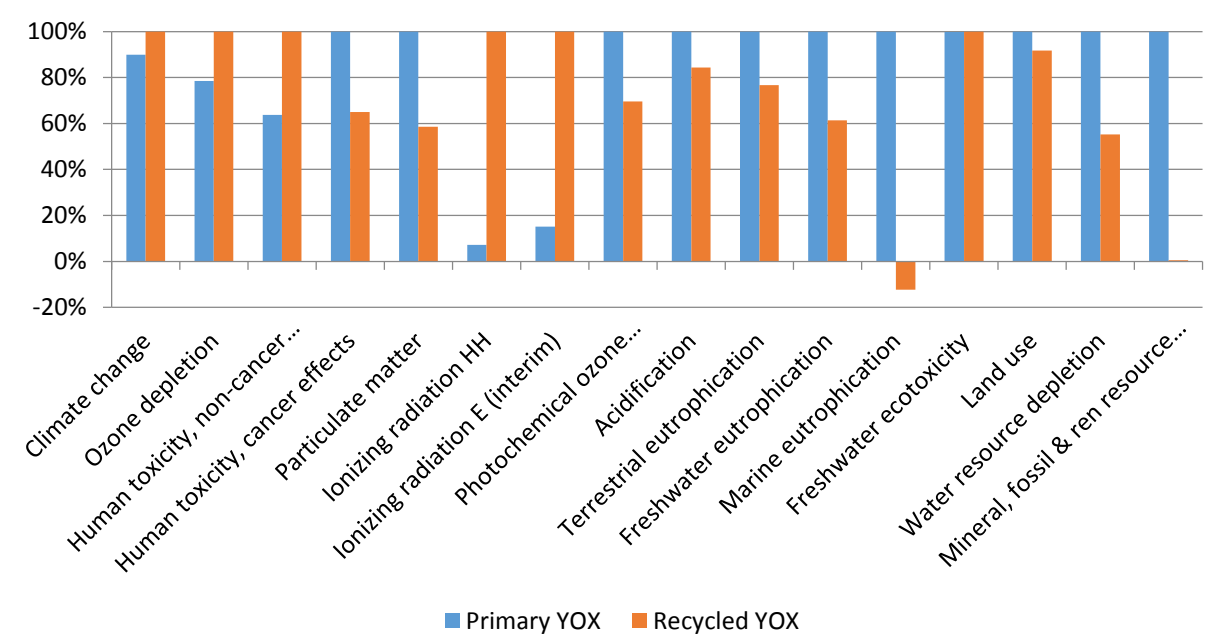


Figure 7C-16 Comparison of the impacts caused by the primary production route and the recycling route of YOX. In this scenario, there is a surplus of europium, which can, therefore, be supplied from stockpiles

## 4.2. Product-oriented LCA on 1 kg of recycled YOX

In this section, the results of the product-oriented LCA are presented. Some questions that focus on the demand of recycled YOX have already been answered in the process-oriented LCA.

### 4.2.1. Quantifying environmental impacts

*What environmental impacts are caused by the demand for 1 kg of recycled YOX?*

Table 7C-13 shows the results for the demand for recycled YOX for the value of  $A = 0.9$ , for the four scenarios of the marginal supplier of europium.

Table 7C-13 Environmental impacts caused by the demand for 1 kg of recycled YOX with a market-price ratio with primary YOX of  $A = 0.9$ . The marginal supplier of europium is either the fluorescent lamp, which competes with LED lamps, halogen lamps or stockpiles.

Impact category	Unit	100% LED	50% LED, 50% halogen	100% halogen	Stockpiling
Climate change	kg CO <sub>2</sub> eq	-4E+01	2E+03	3E+03	5E+01
Ozone depletion	kg CFC-11 eq	5E-06	9E-05	2E-04	9E-06
Human toxicity, non-cancer effects	CTUh	-7E-05	1E-03	3E-03	1E-05
Human toxicity, cancer effects	CTUh	-2E-05	4E-04	7E-04	2E-06
Particulate matter	kg PM <sub>2.5</sub> eq	-2E-02	1E+00	3E+00	5E-02
Ionizing radiation HH	kBq U235 eq	3E+00	5E+01	9E+01	5E+00
Ionizing radiation E (interim)	CTUe	4E-06	2E-04	4E-04	2E-05
Photochemical ozone formation	kg NMVOC eq	-1E-01	5E+00	1E+01	1E-01
Acidification	molc H <sup>+</sup> eq	-1E-01	8E+00	2E+01	3E-01
Terrestrial eutrophication	molc N eq	-4E-01	2E+01	3E+01	5E-01
Freshwater eutrophication	kg P eq	-3E-02	1E+00	2E+00	2E-02
Marine eutrophication	kg N eq	3E+00	4E+00	6E+00	3E+00
Freshwater ecotoxicity	CTUe	-1E+04	2E+05	5E+05	4E+02
Land use	kg C deficit	6E+01	4E+02	7E+02	8E+01
Water resource depletion	m <sup>3</sup> water eq	-4E+00	9E+01	2E+02	1E+00
Mineral, fossil & ren resource depletion	kg Sb eq	3E-01	3E-01	3E-01	3E-01

### 4.2.2. Identifying options for improvement

*How can we reduce the environmental impacts of the demand for 1 kg of recycled YOX, in order to reduce global impacts?*

The market-price ratio  $A$  indicates the share of the demand that is provided by primary resources ( $A$ ) or by additional recycling ( $1-A$ ). Therefore,  $A$  serves as a switch between the impacts caused by the primary and recycling route. A value of  $A = 1$  represents the impacts caused by the primary route. In that case, the environmental impacts of the demand for recycled YOX can only be reduced by reducing the impacts of the primary route. If the market-price ratio has a value of  $A = 0$ , the impacts of the demand for recycled YOX are represented by the impacts of the valorization process. Options for improvement of the valorization process are identified in the process-oriented LCA (Section 4.1.2).

#### 4.2.3. Decision-making

*Does the demand for 1 kg of recycled YOX cause less environmental impacts than the demand for 1 kg of primary YOX?*

This question can be answered based on the results that have been presented up to now. As stated before, the demand for recycled YOX could lead to increased production of YOX via the primary production route when the market-price ratio between recycled and primary YOX is  $A > 0$ . The demand for recycled YOX causes exactly the same impacts as the demand for primary YOX when  $A = 1$ . In the scenario where fluorescent lamps are only competing with LED lights, the primary production route causes lower – or even beneficial – impacts than the recycling route. In that case, a high value for  $A$  results in lower impacts caused by the additional demand for recycled YOX.

When the recycling route performs better than the primary route, a low value for  $A$  makes the additional demand for recycled YOX environmentally beneficial. This is the case when the production of fluorescent lamps is constrained by the availability of europium, and fluorescent lamps compete with both halogen and LED lamps, of which LED lights contribute less than 92% to this mix.

Sometimes it is not clear whether the recycling route is better than the primary route, for example when the recycling route performs better than the primary route on only some impact categories. This is the case when europium is supplied from stockpiles (Figure 7C-16). For this scenario, the impacts of the demand for recycled YOX are calculated with a varying value for  $A$  (Figure 7C-17). Values for  $A$  between 0 and 1 mitigate the difference of impacts caused by the recycling route and the primary production route of YOX.

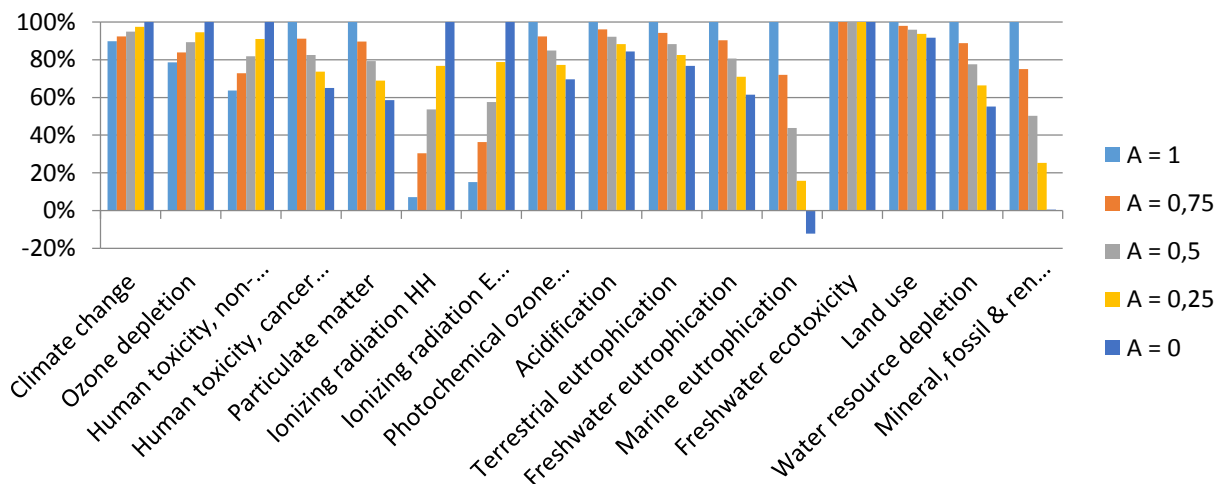


Figure 7C-17 Comparison of impacts caused by the demand for recycled YOX for different values of the market-price ratio  $A$  between recycled and primary YOX. In this scenario, europium is supplied by stockpiles.

### 4.3. Product-oriented LCA on 1 fluorescent lamp

Additional analyses are done on the demand for a fluorescent lamp 1) that does not contain recycled YOX and does not valorize the phosphorous powder at the end of life, 2) that valorizes the powder and 3) that contains recycled YOX.

#### 4.3.1. Quantifying environmental impacts

*What environmental impacts are caused by the demand for 1 fluorescent lamp?*

In this analysis, the impacts that are caused by a fluorescent lamp are calculated. First, the impacts are calculated for a lamp that does not use or produce recycled YOX, for the four different scenarios of the

marginal user of europium. Table 7C-13 shows that the impacts of the lamp are largely influenced by the market situation of europium. It might be counterintuitive that the fluorescent lamp has a higher impact when the lamp competes with less energy-efficient lamps. This is explained by the fact that an additional demand for the lamp results in the fact that someone else is not able to use this lamp and will have to use a less energy-efficient lamp instead. The analysis is continued while eliminating the indirect effects of the use of europium; europium is assumed to be supplied by stockpiles.

Table 7C-14 Environmental impacts caused by the demand for 1 fluorescent lamp that does not use nor supplies recycled YOX at the end of life. The marginal supplier of europium is either the fluorescent lamp, which competes with LED lamps, halogen lamps or stockpiles.

Impact category	Unit	100% LED	50% LED, 50% halogen	100% halogen	Stockpiling
Climate change	kg CO <sub>2</sub> eq	6E-03	2E+00	4E+00	1E-01
Ozone depletion	kg CFC-11 eq	1E-08	1E-07	2E-07	2E-08
Human toxicity, non-cancer effects	CTUh	2E-07	2E-06	3E-06	2E-07
Human toxicity, cancer effects	CTUh	-7E-09	4E-07	8E-07	1E-08
Particulate matter	kg PM <sub>2.5</sub> eq	3E-05	2E-03	3E-03	1E-04
Ionizing radiation HH	kBq U235 eq	1E-02	6E-02	1E-01	2E-02
Ionizing radiation E (interim)	CTUe	3E-08	2E-07	5E-07	4E-08
Photochemical ozone formation	kg NMVOC eq	8E-05	5E-03	1E-02	3E-04
Acidification	molc H <sup>+</sup> eq	5E-04	9E-03	2E-02	9E-04
Terrestrial eutrophication	molc N eq	3E-04	2E-02	3E-02	1E-03
Freshwater eutrophication	kg P eq	9E-05	1E-03	2E-03	2E-04
Marine eutrophication	kg N eq	3E-03	5E-03	7E-03	3E-03
Freshwater ecotoxicity	CTUe	-7E+00	3E+02	5E+02	6E+00
Land use	kg C deficit	2E-01	5E-01	9E-01	2E-01
Water resource depletion	m <sup>3</sup> water eq	-3E-03	9E-02	2E-01	2E-03
Mineral, fossil & ren resource depletion	kg Sb eq	2E-04	2E-04	2E-04	2E-04

#### 4.3.2. Identifying options for improvement

*How can we reduce the environmental impacts of the demand for 1 fluorescent lamp, in order to reduce global impacts?*

A cradle-to-grave LCA is done on the life cycle of 1 fluorescent lamp that does not use recycled YOX and does not valorize the phosphorous powder at the end of life. Note that impacts during distribution and the use phase of the lamp are excluded from the analysis. The contribution analysis of Figure 7C-18 shows how the impacts of this lamp are built up. The largest contributors to impacts are the cradle-to-gate manufacturing processes for the lamp holder and the lamp tube and the waste treatment of the lamp. Recycling of aluminum, mercury, and glass leads to some environmental benefits. Figure 7C-19 shows that aluminum and copper are main contributors to the impacts of the lamp holder. Aluminum is already recycled, and impacts of the lamp could be reduced by recycling the copper as well. The impacts of the lamp tube are mainly caused by the use of YOX, LAP, and glass (Figure 7C-20). This analysis shows that it is indeed relevant to recycle these materials. Negative impacts in Figure 7C-19 and Figure 7C-20 are due to the fact that for the production of several materials heat is used. This heat

is the determining co-product of a co-generation process, where electricity is produced as a co-product. This electricity production can avoid the production of electricity from other sources. Therefore, the use of heat can lead to environmental benefits in the consequential system model of ecoinvent.

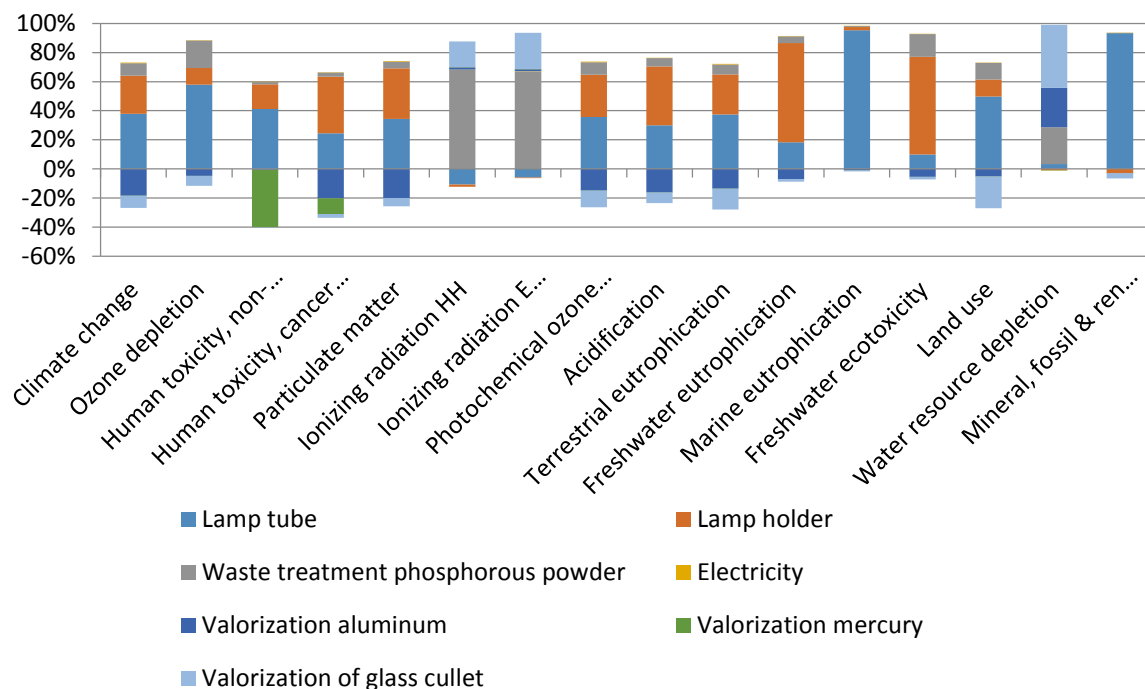


Figure 7C-18 Contribution analysis of the impacts caused by the life cycle of 1 fluorescent lamp

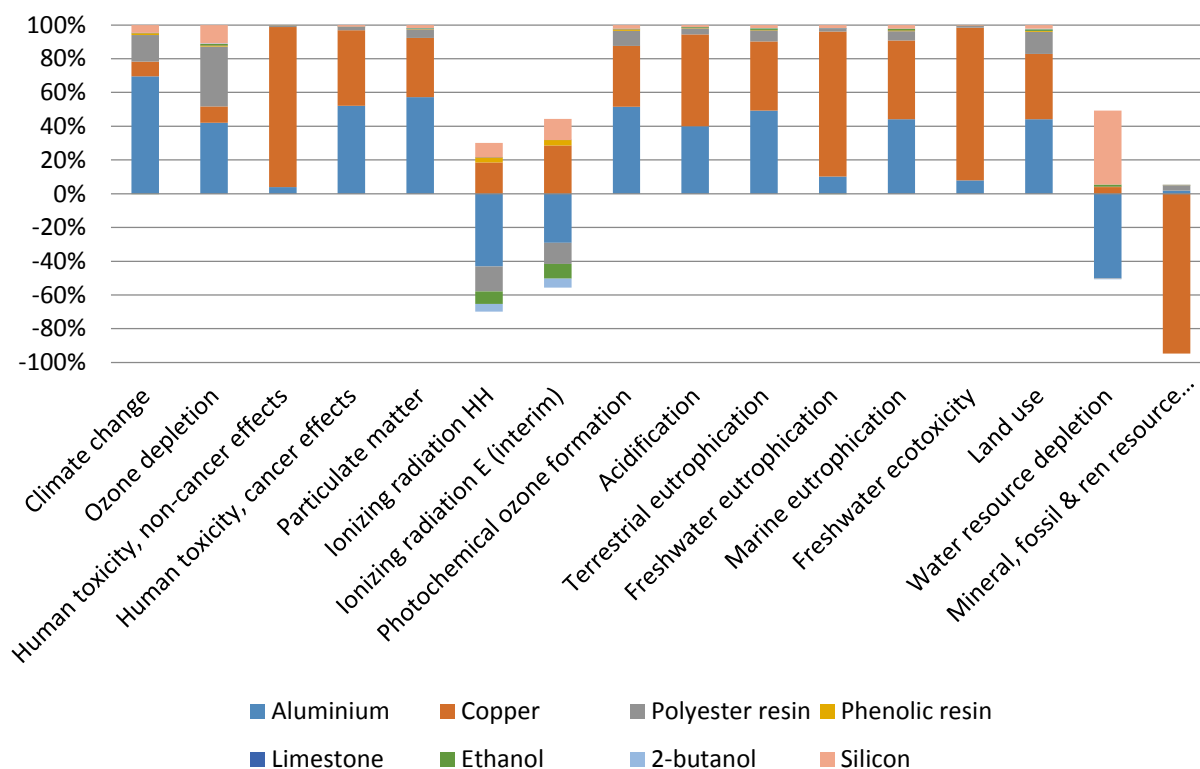


Figure 7C-19 Contribution analysis of the impacts caused by the cradle-to-gate manufacturing of 1 lamp holder

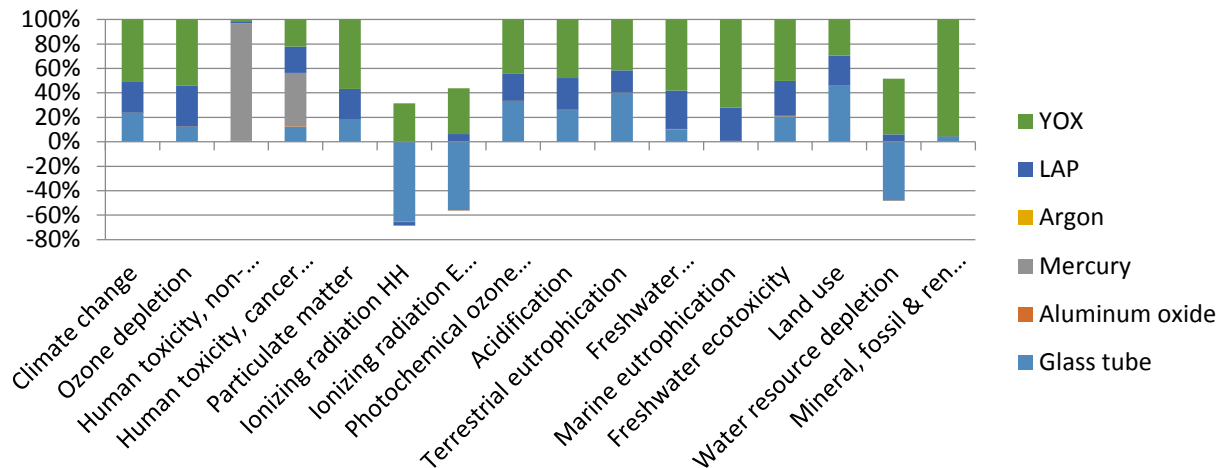


Figure 7C-20 Contribution analysis of the impacts caused by the cradle-to-gate manufacturing of 1 lamp tube

#### 4.3.3. Decision-making

*Does the demand for 1 fluorescent lamp that contains recycled YOX and valorizes the phosphorous powder at the end of life cause less environmental impacts than the demand for 1 fluorescent lamp that only valorizes the phosphorous powder at the end of life or the demand for 1 fluorescent lamp that is not involved with the valorization process at all?*

In the LCA of the fluorescent lamp, there are numerous parameters that can now be adapted: the recycled content, the end-of-life recycling rate, the market-price ratio of the recycled materials and the scenarios for the marginal supplier of europium. Some analyses would give similar results. An overview of typical situations is given in Table 7C-15. Only the scenarios that are represented in bold will be further analyzed. It should be noted that the value for A does not change the results when RRE = 1 and RC = 0.24. In that case, the same quantity of YOX that is recycled at the end of life is used as recycled content, i.e. a closed loop is modeled.

Table 7C-15 Different recycling situations that could be relevant in the life cycle of a fluorescent lamp. The scenarios in bold are further analyzed

Scenario	What happens	What is modeled	Same results as
<b>RRE = 0</b> <b>RC = 0</b>	- Only primary YOX is used - No powder is recycled at EoL	- Additional primary production of YOX - Waste treatment of the powder	
<b>RRE = 1; A = 1</b>	<b>All powder is recycled at EoL</b>	- Additional valorization of the powder	<b>RRE = 1;</b> <b>RC = 0.24;</b> <b>A = any value</b>
RRE = 1; A = 0	All powder is recycled at the EoL	- Waste treatment of the powder	RRE = 0
RC = 1; A = 1	Only recycled YOX is used	- Additional primary production of YOX	RC = 0
<b>RC = 1; A = 0</b>	<b>Only recycled YOX is used</b>	- Additional valorization of the powder	
<b>RC = 1; A = 0.9</b>	<b>Only recycled YOX is used</b>	- 90% additional primary production of YOX - 10% additional valorization of the powder	



The results of the impact assessment for the different marginal suppliers of europium are shown in Figure 7C-21 to Figure 7C-24. Recycling increases the impacts of a fluorescent lamp when this lamp only competes with LED lamps (Figure 7C-21). In this scenario, recycling is only beneficial with regard to marine eutrophication and mineral, fossil and renewable resource depletion. The negative impacts (i.e. benefits) related to the use of primary YOX are due to the fact that electricity use is avoided when LED lamps replace fluorescent lamps.

Figure 7C-22 and Figure 7C-23 show very similar results: recycling of YOX can lower the impact of the fluorescent lamp when fluorescent lamps compete (partly) with halogen lamps. If the recycled YOX has (almost) the same price as primary YOX, it is more beneficial for the lamp to supply recycled YOX at the end of life than to use recycled YOX as a material input. However, if the demand for recycled YOX is low and its market price is as a consequence much lower than the price for primary YOX, any additional demand for recycled YOX leads to reduced impacts. Impacts can even be further reduced if the recycled content is higher than the ratio that corresponds to a closed-loop system (where  $RC = 0.24$ ).

Finally, if fluorescent lamps would play a smaller role in the lighting market than currently is the case, there could be a surplus of europium. In this scenario, europium is supplied from stockpiles. Figure 7C-24 shows that in this case recycling of YOX can barely lower the impact of a fluorescent lamp. Benefits will mainly be achieved with regard to mineral, fossil and renewable resource depletion and marine eutrophication.

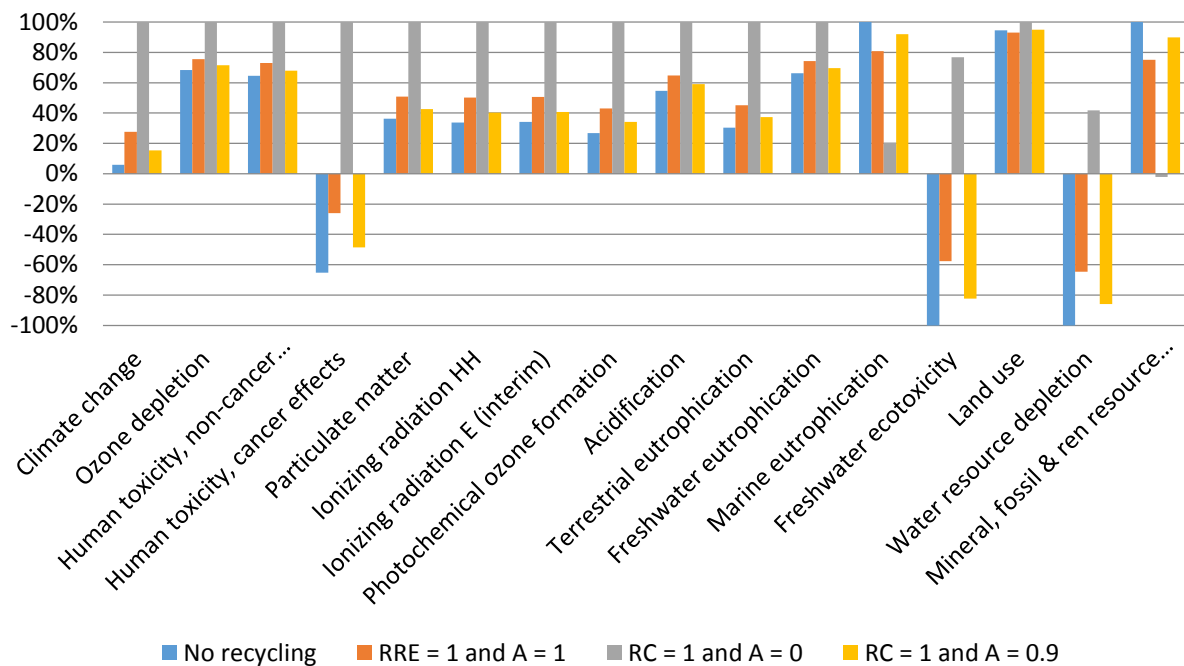


Figure 7C-21 Comparison of the impacts caused by the demand for a fluorescent lamp for different recycling situations. In this scenario, fluorescent lamps only compete with LED lamps

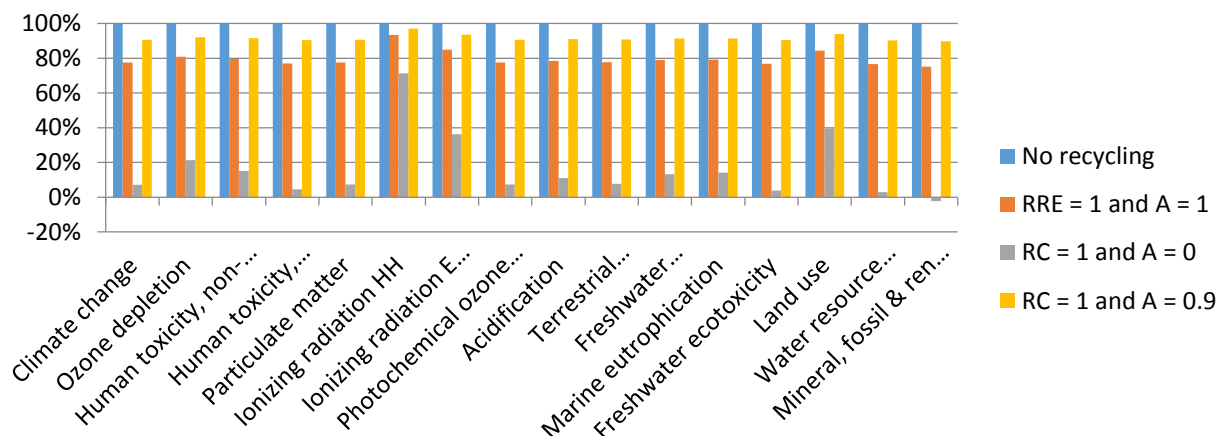


Figure 7C-22 Comparison of the impacts caused by the demand for a fluorescent lamp for different recycling situations. In this scenario, fluorescent lamps compete for 50% with LED lamps and for 50% with halogen lamps

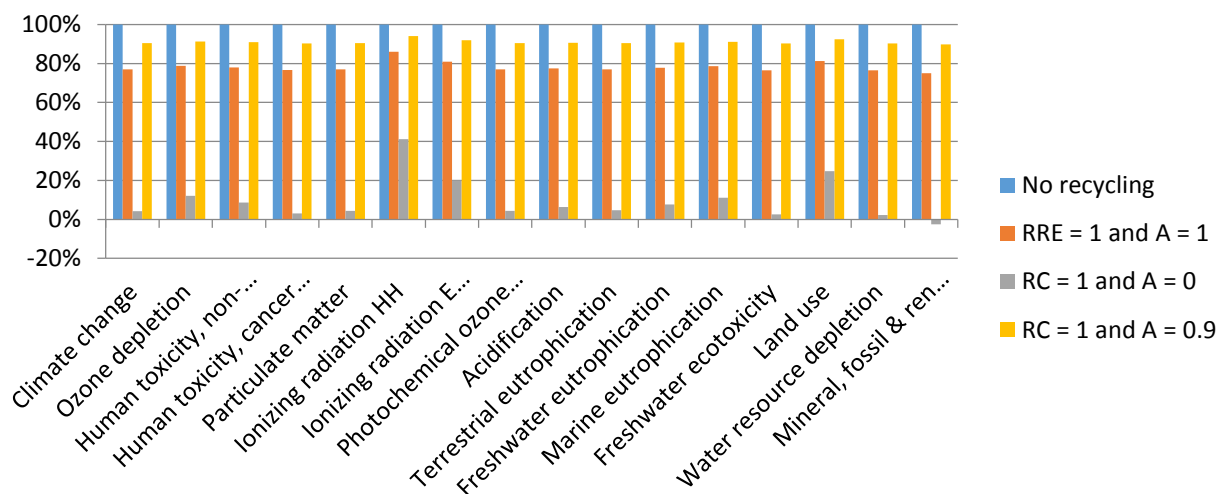


Figure 7C-23 Comparison of the impacts caused by the demand for a fluorescent lamp for different recycling situations. In this scenario, fluorescent lamps only compete with halogen lamps

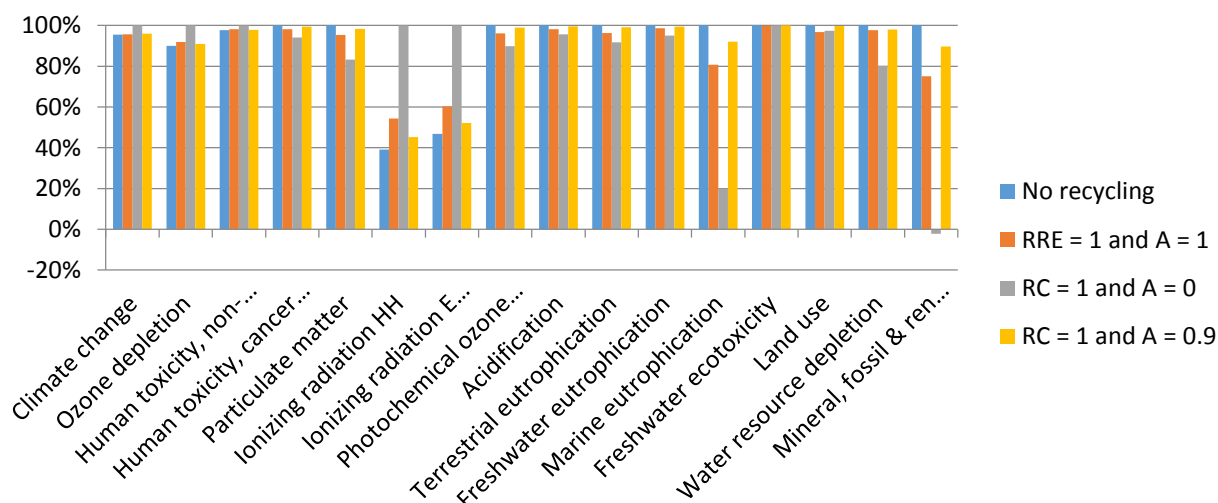


Figure 7C-24 Comparison of the impacts caused by the demand for a fluorescent lamp for different recycling situations. In this scenario, europium is supplied from stockpiles

## 5. Discussion

The main purpose of the case study presented in this chapter was the demonstration of the consequential methodology on the recycling process of phosphorous powder from used fluorescent lamps. It is acknowledged that various assumptions and simplifications are done, that reduce the usability of the results. In this section, several limitations related to the goal and scope and inventory analysis are discussed. Limitations related to the impact assessment have been shortly discussed in Chapter 7B.

### 5.1. Goal and scope definition

Consequential LCA can, in theory, be applied to an unlimited range of applications with different scopes, time frames, mechanisms that are considered, etc. The results of this LCA study are limited by different aspects of the scope definition.

#### *5.1.1. The scale of the decision*

It is assumed that the production of recycled YOX via the recycling route under study is relatively small in comparison to the global production of YOX from primary and recycling routes and that the implementation of the recycling route does not lead to changes in the market situation of the REEs. In that case, the consequences of this decision could be considered to be marginal. Therefore, the implementation of the recycling process affects the same technologies as the decision of a consumer to buy recycled YOX. This assumption also implies that the size of the functional unit is not very relevant, due to the linearity of the consequences with regard to the size of the changes (Weidema et al 2009). Kätelhön et al. (2016) show that results of LCAs that take constraints into consideration are dependent on the scales of production and consumption. If the scale of the functional unit leads to a large increase in the recycling rate of some REEs, the shortage of an element can be transformed into a surplus. Conversely, if a functional unit asks for a large increase in demand for a product for which the demand is constrained, this functional unit might make supply constraints suddenly more relevant than demand constraints. The assumption of linearity between the change and the consequences might then be affected. This is an important side note, of which the influence could be tested by different scenarios with different assumptions for constraints.

#### *5.1.2. The time horizon of the decision*

In this LCA, only current technologies are assumed to be affected by a changing demand for a product. The currently available technologies determine the relative market situation for each REE – e.g. which elements are the determining co-products of mining activities and for which elements supply and/or demand is constrained. However, historical developments in the REE market have shown that the market can rapidly change (Binnemans et al 2013b). In the 1960s, the demand for europium was very high and this was the main output of the Mountain Pass mine in California. At this time, large stocks of LREEs that were produced in excess have been built up. In the 1980s, samarium was the most demanded REE which had led to high prices for this element. Neodymium and dysprosium were barely used at this time (Binnemans et al 2013b). A potential change in the market situation for europium due to an increased market share of LED lamps was already assessed by different scenarios. However, other applications for europium might be found as well, such as security markers (Binnemans and Jones 2014). In the REEs market, research is being conducted to identify new production sources of REEs, either from new mines, new recycling routes as well as the identification of substitutes for the elements (ERECON 2014). The changing market due to the introduction of new applications for REEs results into large changes in prices for the individual elements. This influences the consequential analysis. Changing prices and differences in demand over time strongly influences the identification of the determining co-product, hence, for which element the demand results in increased mining. This is a large limitation on the analysis of the impacts. However, the same limitation is valid in attributional

LCA, where economic allocation is applied to identify the relative responsibility for impacts of each REE. Furthermore, this limitation is not only present in LCA. Investment decisions are always done with the currently available knowledge. If multiple situations could be expected in the future, a scenario analysis can show whether the results are sensitive to these potential developments.

The result for “determining co-product” is very sensitive to parameters that can fluctuate: market prices of all the co-products, market trends, and the (assumptions for the) marginal production costs. This appeared to be critical for the Mount Weld and the Longnan deposit. In consequential LCA we generally consider decision-making over a time frame that includes investment decisions: by avoiding to buy a product, we assume that in the future fewer units of this product will be produced. Therefore, in our case study, we should consider future market developments in the identification of the determining co-product. Lanthanum is the determining co-product of the Mount Weld deposit based on prices of the year 2013 and the assumption that marginal production costs are 80% of the total revenue. However, a surplus of lanthanum is expected in the near future. If lanthanum is indeed the determining co-product of this mine, a surplus might be avoided by decreasing the production of this mine. At the moment there is also a surplus of neodymium. However, this surplus is expected to decrease in the near future. We could expect that the price for neodymium will, therefore, go up, especially in comparison to lanthanum. It is, therefore, more likely that neodymium will be the determining co-product of the Mount Weld deposit than lanthanum. The identification of yttrium, neodymium, and dysprosium as determining co-products is uncertain due to lacking information about up-to-date market prices and marginal operating costs. However, the estimate might be accurate, due to the fact that these materials are considered critical, although supply is following the demand quite well (European Commission 2014a). This suggests that a changing demand for these materials could influence their supply.

#### *5.1.3. Limitations of the identified constraints*

A limited set of supply and demand constraints is investigated, and determining co-products are assumed to be free of supply constraints. This assumption was considered reasonable in a competitive market in the long term. However, the market of REEs is not a typical competitive market. China has a monopoly-like position in the supply of REEs and showed their capability to influence market prices by supply restrictions (Schlinkert and van den Boogaart 2015), while in a competitive market suppliers are price-takers (Weidema 2003). This means that the supply of the determining co-products (yttrium, neodymium, and dysprosium) is probably not fully elastic. In that case, marginal users of these elements should be identified as well, which would reduce their consumption of these elements in response to an additional demand elsewhere. Hence, the same causal loop diagram can be applied.

It is true that constraints can change over time (Weidema et al 2009). Constraints are generally assumed to be fixed; even on the long-term horizon (Zamagni et al 2012). If additional mechanisms are taken into account in a consequential LCA, these constraints could be considered as variable as well. Each mechanism that is not included in the c-LCA is assumed to have no effect, following the *ceteris paribus* assumption (Zamagni et al 2012). In this study, we consider currently available technologies with their current performance level. In this time frame, the consumption of recycled materials is limited by the current technology level of the recycling process and the currently available infrastructure. On the very long term, recycling processes might provide high quality recycled materials and the supply of recycled materials will only be constrained by the production of primary materials, i.e. demand constraints might not be relevant anymore. However, constraints are considered to be stable within in the scope definition of this study. If some constraints are expected to change in the near future, scenarios with different assumptions on the level of constraints could be assessed, similar to the different scenarios of the availability of europium and the market situation of fluorescent lamps.

Changes in demand constraints can be assessed by different values for  $A$ , which was applied to recycled YOX in Figure 7C-17.

## 5.2. Inventory analysis

The inventory that is used in this case study has several limitations as well, which should be considered in the interpretation of the results. In this chapter, crude assumptions have been done to identify the marginal suppliers of the REEs. It is assumed that the marginal supplier is represented by one production route, while in reality a mix of production routes could be affected (Zamagni et al 2012). A correct identification of the marginal supplier requires more data on the different production routes and a deeper understanding of the REEs market. For yttrium, neodymium, and dysprosium, three production routes were identified. However, the same inventory data is used to represent all production routes. Also, the separation process of the REEs is highly simplified. Parameterized data adapted to the ratio of the different REEs in the REE mixture would be ideal to represent the different steps of the separation procedure.

The marginal user must be identified for a product of which the supply is constrained, while the demand is not, e.g. europium. The marginal user is the user that can change his consumption pattern with the least additional costs. In this chapter, it was assumed that the marginal user is the fluorescent lamp. There might be other applications that could change their consumption of europium more easily than this fluorescent lamp. The application in which the price elasticity of demand of a material has the highest (absolute) value is the most sensitive to price changes of this material. This also means that there is probably a good substitute available for this application (Nassar 2015). Holland et al. (2014) found that the demand for fluorescent lamps is strongly sensitive to price changes. This implies that the users of these lamps could easily switch to another product that serves the same function. The degree of substitutability of materials can be indicated by the cross-price elasticity of these materials in a certain application. This term represents the percentage change in quantity demanded of one product with a percentage change in the price of another product. Materials are good substitutes when the cross-price elasticity is high and positive (Nassar 2015). The assumption that terbium can substitute dysprosium on a 1:1 weight ratio is highly uncertain and could be verified with this type of data. Unfortunately, price elasticities are not available for all materials in all applications.

Dependent co-products for which the demand is constrained are in this analysis supplied by stockpiles or avoided waste treatment is modeled. Simplistic assumptions have been done with regard to the avoided waste treatment process. Furthermore, no inventory is associated to (avoided) stockpiling. It should be further analyzed what type of impacts can take place during stockpiling, and how the time dimension of stockpiling can be captured in an inventory dataset.

The analyses in this chapter pointed out that indirect effects can be very relevant in consequential LCA. The choice for the marginal supplier of europium has a large influence on the impacts of the lamp. Initially, the difference in electricity use between the different types of lamp was modeled with the French electricity mix. However, this has led to extreme results showing the benefits of using LED lights and the drawbacks of using halogen lamps. These differences dominated all impact categories of the analysis. Therefore, it was decided to use the Swiss electricity mix instead. This electricity mix is less impactful than the French mix in the consequential system model. The benefits of using LED lights is still present, although now the other effects are less overshadowed by the difference in electricity use. The fact that inventory from the background database gives such a large contribution to the impacts makes it worthwhile to conduct a more detailed study on the marginal user of europium and the indirect downstream effects associated with a potential substitution.

Furthermore, choices in the background system add to the uncertainty of the result. In the ecoinvent system model, technologies are expected to be affected by a change if they are modern, new or current. Other considerations that could contribute to investment decisions are neglected. However, these considerations could be important as well. For example, electricity use is often a relevant contributor to impacts of products. In the consequential system model, the electricity mix of France is dominated by electricity from hard coal. This technology is indicated as modern. However, there are political considerations involved with the development of the national electricity grid that go beyond the technology level of the source. In 2015, numerous countries over the world agreed that greenhouse gas emissions must be reduced during the COP21 conference on climate change in Paris. The issue of climate change might even cause one or two brand new coal-fired power plants being shut down in the Netherlands (NRC 2016). In this context, it is unlikely that electricity from hard coal should be identified as the marginal technology for electricity use.

## 6. Conclusions

The LCA in this chapter aims to calculate what impacts are caused by the production of recycled YOX and the use of recycled YOX in a fluorescent lamp. To this end, based on the goal and scope definition of Chapter 7A, 10 archetypical LCA goal and scope definitions were formulated that all ask for slightly different information from the LCA.

The consequences of an increased valorization of, and an increased demand for, recycled YOX were identified with the help of the Causal Loop Diagram of Chapter 6. In both process-oriented and product-oriented LCA, the determining co-product of processes, the marginal supplier or user of products and substitutes for dependent co-products in high demand must be identified. This appeared to be quite cumbersome, especially in this case study on rare earth elements. REEs are difficult materials to analyze in a consequential LCA due to the fact that these elements are always produced as co-products, the market situation of the elements is quite convergent and substitutes are not easily available.

The process-oriented LCA on the recycling process of YOX showed that several other co-products are produced as well: recycled cerium, lanthanum, terbium, europium, and glass. The effects of an increased supply of these products – and a decreased demand for their primary equivalents – were assessed with the Causal Loop Diagram. This diagram modeled the following effects:

- Recycling of glass avoids the primary production of glass for 7%
- Recycling of cerium and lanthanum avoids the supply of these elements from stockpiles of primary REEs
- Recycling of terbium and europium leads to an increased use of these elements by their respective marginal users

The marginal user of europium was assumed to be the application of a fluorescent lamp. Europium cannot be substituted by another element, but a fluorescent lamp can be substituted by another type of lamp. Due to the uncertainties with regard to the substitute for europium, different scenarios have been analyzed:

- Fluorescent lamps are only competing with LED lamps
- Fluorescent lamps are for 50% competing with LED lamps, and for 50% with halogen lamps
- Fluorescent lamps are only competing with halogen lamps
- Fluorescent lamps are becoming superfluous, and europium is supplied from stockpiles

Downstream electricity consumption is considered as the only difference between these scenarios. The market situation of the fluorescent lamp appeared to be a decisive factor in the assessment of the impacts of the recycling process of YOX:

- Additional recycling of YOX is environmentally impactful when this results in a delayed transition towards more energy-efficient LED lighting
- Additional recycling of YOX is environmentally beneficial when this leads to an accelerated phasing out of less energy-efficient halogen lamps
- If europium would be available in surplus, recycling of YOX causes lower impacts than the primary production of YOX with regard to several impact categories. However, the production of primary YOX causes lower impacts on, among others, climate change

In short, the process-oriented LCA showed that sustaining the availability of rare earth elements by means of a recycling process is only environmentally beneficial as long as these elements enable the increased production of fluorescent lamps, and fluorescent lamps are used to replace less energy-efficient halogen lamps.

In the product-oriented LCA, the effects of the additional demand for recycled YOX were investigated for the use in a fluorescent lamp. Furthermore, it was assessed whether the demand for a lamp that is recycled at the end of life causes lower impacts than a lamp that is not recycled. The market-price ratio  $A$  between the recycled YOX and the substituted primary YOX was used as an indicator to identify whether the demand for recycled YOX is constrained.

The LCA shows that the impacts caused by a fluorescent lamp can be decreased by using recycled YOX when the demand for recycled YOX is low, or by valorizing phosphorous powder at the end of life when the demand for recycled YOX is high. In the current market situation, where the market-price ratio is high and where fluorescent lamps could still displace halogen lamps, environmental impacts of a lamp are decreased if efforts are put in an active participation in the collection of fluorescent lamps and increased recovery of YOX from waste phosphorous powder at the end of life of the lamp. The increased use of recycled YOX in a lamp is not environmentally beneficial over the use of primary YOX, due to the fact that the supply of recycled YOX is constrained. However, the large number of uncertainties of the LCA study and the limitations of the analysis must be taken into consideration when the results are used to support decisions.

This consequential case study has been based on the archetypes of consequential LCA goal and scope definitions as defined in Chapter 7A. These archetypes provided a broad range of research questions that all led to relevant LCA results. The systematic framework of Chapter 3 showed that multifunctional situations could be solved by substitution – and more specifically by the market-driven substitution method that was developed in Chapter 6. The application of the equations of the market-driven substitution method has been demonstrated in this case study. The market-price ratio  $A$  proved to be a useful indicator to identify whether additional recycling substitutes the production of primary materials or avoids waste treatment.

This case study provided a broad range of results. In Chapter 8 it is discussed how these results can serve objectives of industrial interest.



## Chapter 8: Modeling in LCA for goals of industrial interest – lessons learned from the case studies

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### 1. Introduction

The case study of Chapter 7 has demonstrated the differences in the application and the results of an attributional and consequential LCA. These differences are further discussed in this chapter. The question remains which LCA approach serves best which goals of industrial interest. In Chapter 2, potential motivations of a company to conduct an LCA were introduced. It was argued that these goals reflect the sustainability of the operations of a company, which could be assessed with an attributional LCA. In the current chapter, the results of the case study of Chapter 7 are interpreted from the perspective of an industrial actor.

In this chapter, two types of industrial interests are distinguished. It is considered that LCA results can be used for internal objectives that are within a company's area of influence. These objectives include internal innovation, product design, process optimization, supply-chain management, and marketing – for example via Environmental Product Declarations. Furthermore, LCAs can serve external objectives of industrial interest. Companies can, for example, share LCA results with public policy makers. The industry is affected by policy makers by legislation, regulation or taxes. Furthermore, policy makers can support the industry by stimulating a situation in which recycling is not only environmentally, but also economically beneficial. This chapter discusses the use of attributional and consequential LCA for both internal and external objectives of industrial interest.

### 2. LCA approach to support internal objectives of industrial interest

This section focuses on internal objectives of industrial interest. Internal objectives here refer to the area of influence of the company. This comprises internal innovation and process optimization, as well as the connection of the company with their suppliers and clients. These connections can be established by contractual agreements and marketing. The application of the theory of attributional and consequential LCA to the case study of rare earth elements in Chapter 7 has provided several insights with regard to the choice between these methods and between a product-oriented and a process-oriented LCA. First, the comparability of the results is discussed. Then, the applicability and interpretation of the attributional and consequential LCAs are discussed with regard to internal objectives of industrial interest.

#### 2.1. Comparability of results of different LCA approaches

Table 8-1 shows the results of climate change and resource depletion of the attributional and consequential analyses that were done in Chapter 7. The results seem similar in the process-oriented LCA with the expanded functional unit. In fact, elementary flows in the foreground subsystem are the same in the process-oriented LCA. However, a different background database is used: background processes are modeled by APOS in the a-LCA and by substitution in the c-LCA. The results of the product-oriented LCA on 1 kg of YOX are more divergent, as allocation is also applied in the foreground subsystem according to the same method as the respective background systems.

Similar results between attributional and consequential LCAs are in many cases merely a coincidence. Technically, the results can be similar if the demand for a product is analyzed that can only be produced by one production route, and the foreground system contains only elementary flows or all ingoing or outgoing intermediate flows are purely monofunctional flows, upstream as well as downstream. This situation is highly unlikely, as, in reality, many processes are multifunctional.



Table 8-1 Results for selected impact categories from the LCAs in Chapter 7

	Climate change (kg CO <sub>2</sub> eq)	Mineral, fossil & ren resource depletion (kg Sb eq)
<i>Functional unit: The production of 1 kg of recycled YOX, 2.05 kg of recycled glass, 0.18 kg of recycled lanthanum, 0.14 kg of recycled cerium, 0.07 kg of recycled terbium, 0.0029 kg of recycled europium and the treatment of 9.92 kg of phosphorous powder from used fluorescent lamps.</i>		
Attributional LCA	6E+01	2E-03
Consequential LCA	6E+01	2E-03
<i>Functional unit: The demand for 1 kg of recycled YOX</i>		
Attributional LCA	3E+01	2E-02
Consequential LCA*		
• 100% LED	-4E+01	3E-01
• 50% LED, 50% halogen	2E+03	3E-01
• 100% halogen	3E+03	3E-01
• Stockpiling	5E+01	3E-01

\*The large range of results is due to different scenarios for the marginal user of europium, which is modeled by large differences in downstream electricity use.

## 2.2. Attributional LCA to support industrial interests

In the attributional case study of Chapter 7B, allocation was avoided by system expansion in the process-oriented LCA. In the product-oriented LCA, allocation was applied by “allocation at the point of substitution” (APOS). These approaches are discussed in this section and the APOS method is compared to other allocation procedures. It is considered that this discussion is of industrial interest, due to the fact that several industrial sectors have a pronounced preference for certain allocation procedures - as stated in Chapter 2. Therefore, the discussion is included in this chapter, rather than in the discussion of the case study of Chapter 7B.

### 2.2.1. Process-oriented and product-oriented LCA

System expansion can be applied in process-oriented attributional LCAs, which can avoid the need to apply partitioning. The benefits and limitations of a process-oriented and product-oriented attributional LCA are summarized in Table 8-2. It is concluded that both approaches have their merits and limitations. It depends on the intended use of the LCA results which LCA approach is most useful, and whether the limitations of the approach are acceptable.

### 2.2.2. Application of APOS

It was demonstrated in Chapter 7B how APOS can be applied to recycling situations. We shortly discuss this allocation procedure in the context of industrial applications.

#### 2.2.2.1. Data requirements

To correctly execute an assessment with APOS, more data are needed than when other allocation procedures are applied, such as the cut-off approach or the substitution method. This is especially the case when a recycled material is used as an input in the product system. Data collection is a time-consuming activity and can act as an impeding factor on the applicability of an LCA approach by a company. Problems in data collection could be reduced if databases, such as ecoinvent, would include the end-of-life treatment of materials that are often recycled. Data on production volumes of different kinds of product systems that provide the same recycled materials would help to generate an average mix of impacts that is attributed to the recycled material. In some situations, the cut-off approach could be applied to simplify the assessment. This is further discussed in Section 2.2.3.1.

Table 8-2 Characteristics and limitations of process-oriented and product-oriented attributional LCAs

Modeling differences	Process-oriented LCA	Product-oriented LCA
<i>Allocation procedure</i>	System expansion	Partitioning
<i>Incoming waste flows</i>	Intermediate inputs with unknown cradle-to-gate impacts can be included in the functional unit as “the treatment of [ingoing flow]”	The point of substitution of the incoming intermediate flow should be identified. Extra modeling of the product system that supplies the intermediate flows is necessary, and partitioning between the co-products of the previous product system is required.
<i>Outgoing co-products</i>	Intermediate outputs that are considered to be co-products can be included in the functional unit as “the production of [outgoing flow]”	The point of substitution of the outgoing intermediate flow should be identified. Extra modeling is necessary if additional treatment is needed before the intermediate flow is considered to be a co-product. Partitioning between the co-products of the product system is required.
<i>System boundaries</i>	System boundaries can be drawn at company boundaries	System boundaries are not always the same as company boundaries
<i>Comparison of products</i>	Two products cannot be directly compared to each other, due to the fact that impacts are not attributed to individual products	Two products can be directly compared to each other
<i>Further use of results</i>	Results cannot be used in LCA studies of the downstream application of a product	Results can be used in LCA studies of the downstream application of a product

#### 2.2.2.2. Interpretation and communication of the results

The APOS method was built on a set of definitions and axioms that are considered to be reasonable and acceptable. However, the method could still give results that are counter-intuitive and difficult to communicate.

From the hotspot analysis of 1 kg of recycled YOX from fluorescent lamps, it appeared that the recycled YOX is accountable for impacts of the fabrication of the lamp tube and the lamp holder. For example, recycled YOX has a high impact on human toxicity (non-cancer effects), which is due to the consumption of mercury in the lamp tube. Furthermore, the recycled YOX is also partly responsible for impacts due to the use of copper and aluminum in the lamp holder. It could be difficult to understand why the recycled YOX is responsible for the consumption of these materials, as these products are completely different than YOX.

This accountability for impacts can be explained in terms of sustainability. In Chapter 2, it was introduced that companies have an interest in assessing the sustainability of a product’s value chain. The user of recycled YOX that contains elements from the end-of-life fluorescent lamps engages himself in the supply chain of the fluorescent lamp. Indirectly, the lamp is supported by the user of recycled YOX: the revenue for the REE mix could, in theory, make the product system of the lamp – including its waste treatment – more viable. A buyer of the REE mix tacitly agrees with the upstream impacts during the production of the lamps. If the user of the REE mix does not want to support these

types of impacts – for example, as it could affect the company’s image – he should do some effort to identify whether these take place in his supply chain. To avoid accountability for environmental impacts, he could choose to not engage with any products that are produced by a product system in which impactful materials are used. The sustainability of a product’s value chain is not only related to the image of a company. If an upstream process is involved with high environmental impacts, this process might be affected by future regulations or environmental taxations. This could pose a risk to the viability of this supply route. A company that relies on the consumption of recycled YOX has an interest in knowing that the YOX is closely related to the environmental impacts of a fluorescent lamp. Developments on the market of lamps could inform the company whether this supply route is “future proof”.

The allocation procedure “allocation at the point of substitution” calculates the impacts that take place in the value chain of a product. This could inform a company on the sustainability of the value chain.

Even though some effort could be done to explain the responsibility for impacts of a product, the existence of counter-intuitive statements is inherent to the fact that we wish to attribute all impacts to all economic activities (Heijungs 1997). The results of an attributional LCA with APOS can show impacts that the actors in a product system do not feel responsible for. However, Heijungs states that being responsible is not synonymous to having influence (Heijungs 1997).

### 2.2.3. Comparison of APOS with other approaches

Chapter 4 showed that, instead of the APOS method, the allocation procedures that are most often recommended to model recycling in an attributional LCA are the cut-off approach and the end-of-life recycling method.

#### 2.2.3.1. Comparison with the cut-off approach

In the cut-off approach, the recycled material that is used as a material input is considered burden-free. There is not one correct location to put the system boundary (Zamagni et al 2008): this could be done at the moment where the material is produced, or at the recycling facility after transport, or after the recycling process. In the context of the case study of Chapter 7B, this could imply that either the phosphorous powder is considered burden-free, or the recycled REE mix is burden-free (see Figure 7A-1).

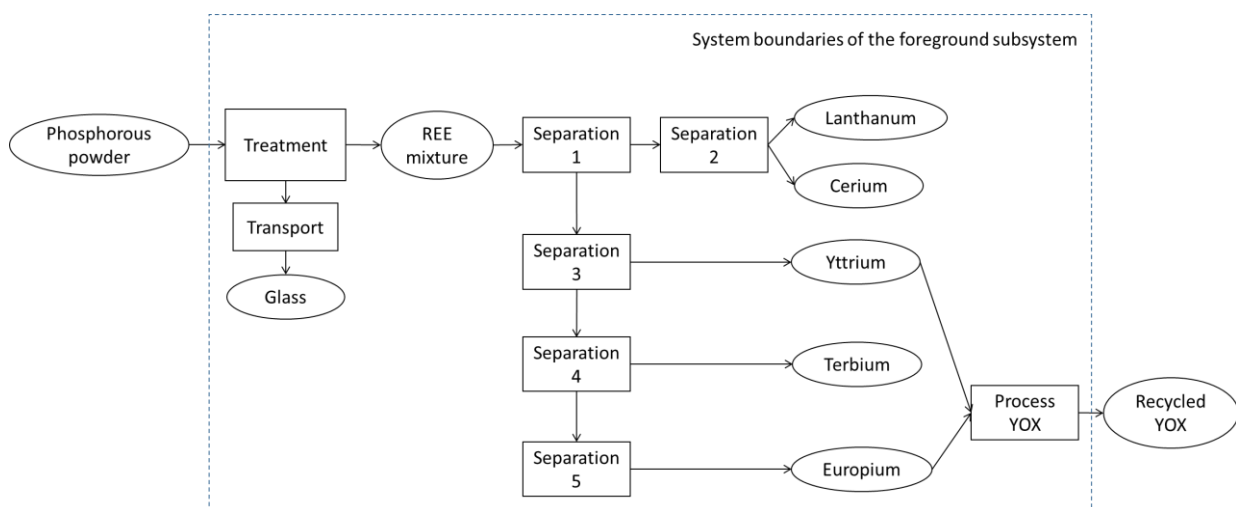


Figure 8-1 System boundaries of the foreground subsystem of the case studies of Chapter 7B and 7C

If the phosphorous powder is burden-free, the product-oriented analysis could resemble a process-oriented LCA. In the process-oriented LCA, the waste that is used as a material input does not carry any impacts, as the treatment of this material is part of the functional unit. If the process is modeled up to the production of 1 kg of recycled YOX, the impacts of the recycling process could be fully attributed to YOX, while the other co-products are again burden-free. However, again, a choice should be made regarding the system boundaries of the recycling procedure. Only reactors 1, 3, 4 and 5 are required to produce YOX. If the system boundary would be put at the same place as for the phosphorous powder – i.e. at the moment where an intermediate flow that is valorized is generated, separation 2 falls outside these boundaries and is part of the product system of lanthanum and cerium. These co-products are therefore not entirely burden-free. Then, the results would differ from the process-oriented LCA where separation 2 would be part of the analysis in the production of YOX.

Another possible location of the system boundary is at the moment when a useful product is generated. In that case, the treatment of the phosphorous powder is modeled by the fluorescent lamp and the REE mixture is burden-free. The system boundary now coincides with the point of substitution. In Chapter 3 we argued that the cut-off approach and APOS could give the same results if the allocation factor of the co-product is 0%. In this case study, the allocation factor of the REE mix was calculated to be 1.10%. This is very close to 0%, so a simplification might be to consider the REE mix burden-free. However, this simplification cannot be justified in this case. The hotspot analysis of the product-oriented LCA indicated that the impacts attributed to the REE mix contribute largely to the impacts of the recycled YOX. If this would be ignored, as in the cut-off approach, the impacts attributed to recycled YOX would be strongly underestimated. Even though 1.10% seems like a small responsibility for impacts, this cannot be concluded if the total amount of impacts for which the product is partly responsible is not known. A deeper analysis of the product system that supplied the co-product is needed. Therefore, the preference is given to allocation at the point of substitution over the cut-off approach.

It might be possible to estimate beforehand whether the cut-off approach could be applied to simplify the analysis and reduce data collection. The mass flows of the product systems of the lamp and the recycling process in Chapter 7B indicate that 1 kg of recycled YOX is dependent on the production of 5000 fluorescent lamps. This is due to the fact that a lamp uses very small quantities of phosphors, while the unitary price of phosphors is relatively high. This suggests already that the product system of the lamp cannot be ignored in the calculation of impacts of recycled YOX. Comparing this to the recycled glass from the lamp, the allocation factor is similar as recycled REEs, while the quantity of recycled glass is much higher: the impacts per kilogram of recycled glass are much smaller than the impacts per kilogram of recycled REEs. Therefore, in a situation in which the recycled product represents a large fraction of the primary product, the use of the cut-off approach might be justified if the allocation factor of the recycled material is close to 0%. Regarding recycling in different industrial sectors, this might, for example, be the case for recycled tires.

The cut-off approach could be applied as a simplification for APOS in a situation in which the recycled product represents a large fraction of the primary product and its economic value is relatively low.

#### 2.2.3.2. Comparison with the end-of-life recycling method

ISO 14044 states that when open-loop recycling takes place, and the material properties of the recycled product are the same as the primary product, a closed-loop allocation procedure can be applied. This could be interpreted as the end-of-life recycling method (ISO 2012): all recycled products that the product system produces could substitute the production of the primary equivalent of this

product. The impacts of the substituted primary production are modeled as “avoided impacts” – i.e. negative impacts – in the life cycle under study. The application of the end-of-life recycling method in an attributional LCA has been recommended by several guidelines (Chapter 4) and is supported by the metals sector (Atherton 2007).

In Figure 8-2 we show the impacts of a lamp modeled by the end-of-life recycling method and APOS. The results show that the methods provide the same results if the amount and type of recycled material that is used in the lamp is equal to the amount and type of recycled materials produced at the end of life, which is the case when the recycled content of YOX is 25%. However, the analysis would be very limited if the end-of-life recycling method would always be applied – also when the recycling rates do not resemble a closed-loop situation. Figure 8-2 shows that the impacts of the lamp are higher when less recycled material is used than produced, and impacts are lower when the recycled content is higher. This type of information cannot be obtained with the end-of-life recycling method, as this method assumes that the recycled content and the end-of-life recycling rate are equal. As in most case studies these rates are not equal, allocation at the point of substitution is preferred over the substitution method.

Atherton (2007) argues that a higher content of recycled metals in a product does not lead to increased recycling, but might lead to a less efficient – economically and environmentally – use of recycled materials. This is due to the fact that there is a limited availability of recycled metals. It is true that an increased recycled content does not necessarily lead to environmental benefits, which is assessed with a consequential LCA. However, an increased recycled content can make a product more sustainable. The fact that the metal market is increasing and there is a lack of recycled metal – sometimes due to a long lifetime of products – indicates that metal products are currently heavily dependent on the primary production of metals. The growing demand for metals makes the use of metals unsustainable. This might change in the future when applications using metals reach the end of life and more recycled metal becomes available. In that case, the recycled content might approximate the end-of-life recycling rate, and metal products become less dependent on primary metal production.

The end-of-life recycling method assumes that the recycled content does not lead to environmental benefits. However, the recycled content can make a product more sustainable, which is assessed by the APOS method.

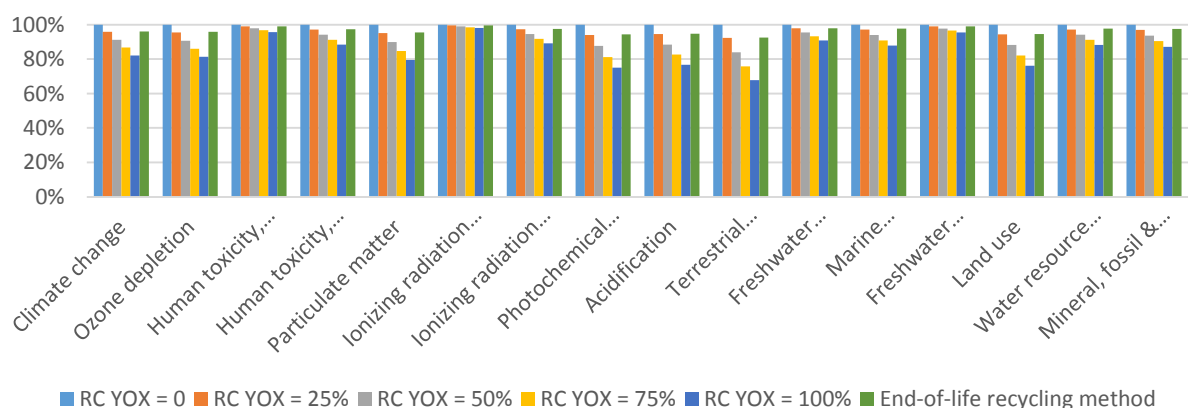


Figure 8-2 Comparison of the impacts attributed to the demand for 1 fluorescent lamp containing different quantities of recycled YOX, modeled with APOS, and to the demand for 1 fluorescent lamp that recycles the powder at the end of life, modeled with the substitution approach. In the APOS method, the recycled content (RC) of YOX is varied between 0% and 100%. The recycled content of other recycled materials (glass, aluminum, mercury and other REEs) is kept constant at the level of RC = RRE. The results are represented relative to the alternative with the highest impacts, which is set to 100%

#### *2.2.4. Improving attributional LCA by consequential thinking*

Although attributional and consequential LCA use different modeling methods, consequential modeling could be used to improve an attributional analysis in which system expansion is applied. In a comparison of a recycling system with alternative processes of waste treatment and primary production, ideally, the product systems are fully comparable, i.e. they provide the same functions. However, in practice, recycled materials are quickly assumed to have the same functionality as primary materials. For example, this assumption was done in the comparison of glass cullet and primary glass in the attributional LCA of Chapter 7B, where the production of glass cullet was one of the functions in the expanded functional unit. Indirect effects of using recycled material instead of primary material are not always known and might not always be taken into account in the expanded system. Of course, in an ideal attributional LCA, the functional units are described in sufficient detail to consider a changed consumption of ancillary materials in the alternative product system as well. Elements from the Causal Loop Diagram of the consequential approach can be used to identify the comparability of the product systems. In the consequential LCA of Chapter 7C, it appeared that glass cullet cannot directly substitute primary glass. Based on the market-price ratio, it was assumed that the glass cullet could substitute 7% of the inventory of the primary production route of glass. This assumption was considered useful in the expanded functional unit of the attributional LCA as well.

### **2.3. Consequential LCA to support industrial interests**

In Chapter 2 it was stated that attributional LCA is considered useful for industrial objectives. Besides, most of the guidelines that were reviewed in Chapter 4 recommend an attributional approach. However, the consequential case study of Chapter 7C showed that this LCA approach provides useful information for companies as well. This is further discussed in this section.

#### *2.3.1. Promoting environmentally beneficial activities*

In the consequential case study of Chapter 7C, both a process-oriented and a product-oriented LCA were conducted. A process-oriented c-LCA provides information on the environmental impacts that are caused by the recycling activity. The results of the case study of the recycling process of YOX showed that the recycling process does not only cause lower impacts than the primary production route of YOX; the recycling process even avoids environmental impacts if the recycled rare earth elements are used to produce more energy efficient lamps. This type of information is useful for a company that organizes the recycling activity. The recycler plays a role between the producer of the waste and the consumer of the recycled product. Therefore, it is not necessary to know whether the additional supply of the waste or the additional demand for the recycled product initiates the recycling process. The recycling company can use the results of the consequential LCA to strengthen its reputation of being environmentally conscious. Furthermore, the LCA results could support a request for subsidies, which is further discussed in Section 3.2.

The product-oriented consequential LCA calculated the environmental impacts that were caused by the additional demand for recycled YOX. The high market-price ratio  $A$  between recycled YOX and primary YOX indicated that supply constraints are more relevant than demand constraints in the market of recycled YOX. This means that the additional demand for recycled YOX does not result in the additional recycling of phosphorous powder. Instead, the increased demand for recycled YOX results in a decreased use of this product by other applications that now will have to use primary YOX. In fact, it is the additional supply of phosphorous powder at the end of life that leads to increased recycling and an increased availability of recycled YOX, which could avoid the production of primary YOX. This type of information is useful for a company that uses YOX in its products, such as the fluorescent lamp. If a company is involved in the recycling activity of YOX – which is environmentally beneficial – the company could use this information for marketing to the consumers of the lamp. A label that refers to



the recycled content of the lamp is, in this case, misleading, as it is not the recycled content that leads to environmental benefits. However, the recyclability of the lamp could be promoted and the company could display its active participation in collection and recycling schemes. If the market situation of recycled YOX would be different – for example in the case of a lacking demand – the market price of recycled YOX might be lower than the price of primary YOX. In that case, the use of recycled YOX is environmentally beneficial and the producer of the fluorescent lamp can promote the recycled content of YOX instead of its recyclability.

- Recycling companies can use the results of a process-oriented c-LCA to demonstrate the environmental benefits of the recycling activity.
- Companies that use recycled materials in their applications can use the results of a product-oriented c-LCA to promote the recycled content or the recyclability of a product at the end of life – based on the market-price ratio  $A$  between the recycled and the primary product:
  - The recycled content of a product can be promoted when  $A < 1$
  - The recyclability of a product can be promoted when  $A > 0$

### 2.3.2. Consequential LCA to inform industries

It was stated before that a company is not necessarily accountable for the impacts that are caused by its activities, which is assessed in a consequential LCA. However, if the use of certain materials causes a high impact elsewhere, this could influence the viability of the company in other ways. As an example, we can take the rare earth element europium. The processes that are of interest in an attributional and a consequential LCA on the demand for europium are represented in Figure 8-3. Europium is mainly used to produce the phosphor YOX, which is difficult to substitute. Figure 8-3 shows that there are different types of applications that use europium: fluorescent lamps, video screens, the nuclear industry and fluorescent dyes. For each application, an attributional LCA shows that the use of europium is associated with impacts from mining or recycling processes and a consequential LCA shows that the demand for europium leads to a decreased production of fluorescent lamps.

A producer of fluorescent lamps learns from this assessment that the use of europium might lead to the substitution of his technology by another technology, such as halogen lamps or LED lights. This is of course not in the interest of the company. As long as the fluorescent lamps are substituted by halogen lamps, the company can still remain viable. Consumers might prefer fluorescent lamps due to their high efficiency, and they might be willing to pay a higher price due to savings on electricity use. Governments might be motivated to support the industry of fluorescent lamps due to their contribution to reducing greenhouse gas emissions.

Any other company that uses europium in this market situation might experience more drawbacks. The producer of video screens would still have to pay a high price for this element, without receiving the financial support that the fluorescent lighting industry might receive. However, if fluorescent lamps are about to be substituted by LED lamps, there might be no external motivation to support the production of fluorescent lamps. In this potential future situation, the current shortage of europium might be transformed into a surplus (Binnemans 2014), which would be reflected in the prices. Users of europium will be less accountable for impacts due to a more favorable economic partitioning of mining impacts. The additional demand for europium causes lower impacts as well because europium might be supplied from stockpiles. The identification of the marginal user and the downstream environmental impacts that take place due to substitution in consequential LCA can help a company to identify whether its position might be put in danger by a continuous use of the material – hence, whether the use of this material is sustainable.

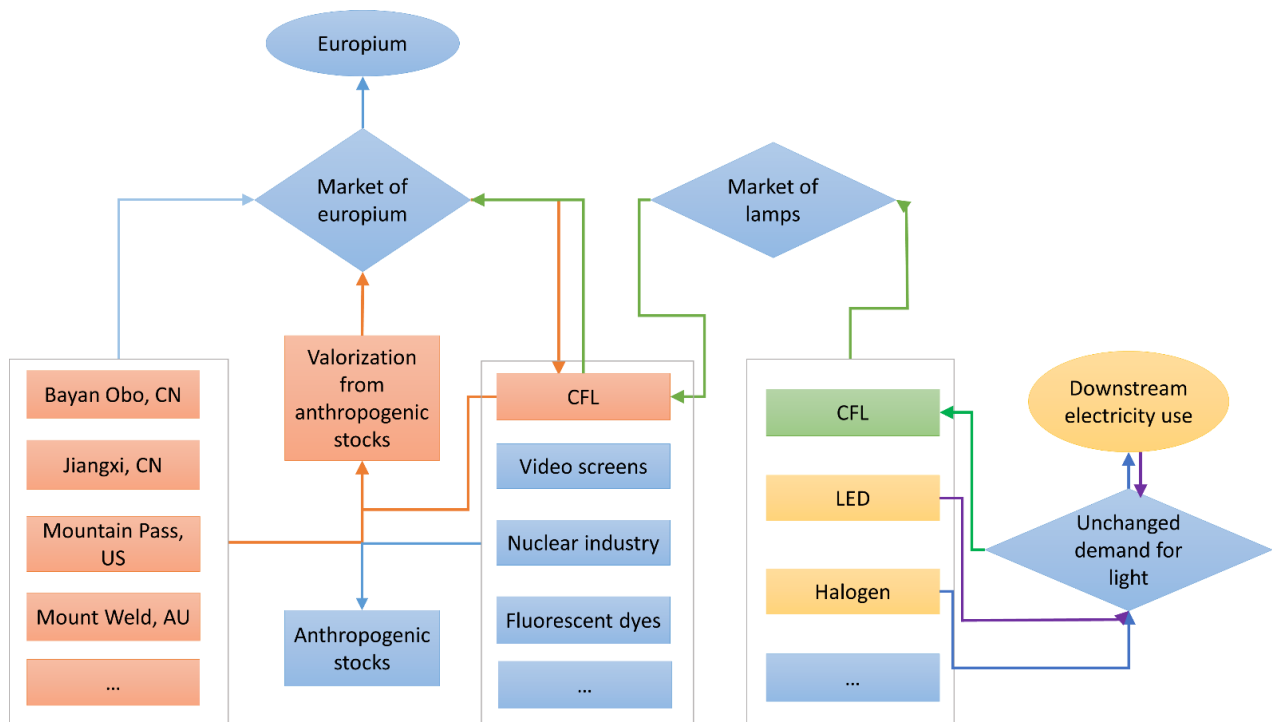


Figure 8-3 Processes of interest in an LCA study on the demand for europium. Processes in orange are of interest in an attributional study: the demand for europium is dependent on co-production from several mines or on the recycling of fluorescent lamps. Processes in green are of interest in a consequential study: the demand for europium does not affect primary mining or valorization; instead, it leads to a decreased use in fluorescent lamps, which can be substituted by halogen lamps. This substitution leads to an increased consumption of electricity in the use phase of the lamp

### Consequential LCA for Life Cycle Sustainability Assessment

In Chapter 2, a framework for Life Cycle Sustainability Assessment was introduced, developed by Sonnemann et al. (2015) and Gemechu et al. (2016). This framework shows that the sustainability of resource use can be assessed on three levels: an environmental, an economic and a social level. While the environmental level can be assessed by an environmental LCA, the economic level is assessed by a resource criticality assessment. This assessment considers supply risks related to geological scarcity, geopolitical factors and vulnerability to supply restriction. Recycling of rare earth elements is often considered a necessity due to their status as “critical” materials (ERECON 2014). Although REEs are often considered as critical as a group (European Commission 2014a), some elements are considered more critical than others. The US Department of Energy identified dysprosium, neodymium, terbium, europium and yttrium as critical for the transition towards cleaner technologies in the next years (U.S. Department of Energy 2011). Interestingly, these elements contribute largely to environmental impacts in the consequential LCA of Chapter 7C. This is due to the fact that yttrium, dysprosium, and neodymium are determining co-products of mines, and europium and terbium are supplied by their marginal users. An increased demand for terbium could lead to increased mining of dysprosium. The consumption of europium could lead to high environmental impacts when fluorescent lamps compete with halogen lamps. If fluorescent lamps only compete with LED lights, the demand for europium causes very low impacts or is even beneficial for the environment. This is caused by the fact that a shortage of europium could lead to an accelerated transition towards LED lights, which are environmentally preferable over fluorescent lamps – considering only their electricity consumption.

The fact that the criticality assessments of resources and the consequential LCA show similar results is not surprising, as several of the indicators for the assessments are the same. Very recently, Graedel and Reck (2016) have reviewed the implementation of criticality in the past six years. They give an extensive overview of criticality studies between 2008 and mid-2014. They urge that criticality is



situation-dependent, and that there is a need for a more uniform methodology. They criticize the trend to assume single criticality factors for diverging situations and they provide an overview of desirable aspects of criticality determinations, such as substitutability, the production of co-products, geopolitical considerations and the question whether recycling can affect the demand for primary products. These elements are also increasingly developed in consequential LCA. In consequential LCA, the production of co-products, the relative prices of the REEs, the market trends, the substitutability of elements in different applications and the nature of the substitutes all contribute to the life cycle inventory related to the consumption of an element. In the consequential LCA of Chapter 7C, the supply of yttrium, dysprosium, and neodymium was assumed to be fully elastic. However, it was discussed that this might not be a realistic assumption due to the monopoly-like position of China. The REE crisis of 2011 showed that prices can largely be influenced by the decreased export from China, i.e. the producers are *not* price-takers. The consequential analysis can be improved by identifying long-term price elasticities of supply of the elements, marginal users of yttrium, dysprosium and neodymium and the substitutes that will be used if less of these elements become available. This additional data would reflect the supply risks that are also assessed in the resource criticality assessment.

In short, consequential LCA can acknowledge the existence of supply risks due to the relative inelasticity of supply. Demand constraints can indicate whether there might be shortages or surpluses of the material, and the marginal user and the available substitutes indicate whether the material is necessary for a transition towards cleaner technologies. This suggests that a consequential LCA can indicate whether the continuous use of a material by a company is sustainable from an economic perspective, or whether the future viability of this company might be compromised.

Consequential LCA shows similarities with a Resource Criticality Assessment. Hence, a c-LCA could inform a company whether its use of resources is sustainable from an economic point of view.

### 3. LCA approach to support external objectives of industrial interest

In the previous section, industrial applications of LCA results within the area of influence of a company were discussed. Companies can however also use LCA results to inform public policy makers, which can in their turn influence the industrial playing field by regulations and legislation.

#### 3.1. Attributional and consequential LCA to communicate with public policy makers

Whether policy-making should be based on the results of attributional or consequential LCA is often discussed in the LCA domain, for example by Plevin et al. (2014b), Suh and Yang (2014), Dale and Kim (2014), Plevin et al. (2014a), Hertwich (2014), and Brandão et al. (2014). While attributional and consequential LCA can both be useful to inform a company about the sustainability of their operations, similar conclusions can be drawn for policy makers. We refer again to the results of the attributional and consequential LCAs of recycled YOX from fluorescent lamps (Chapter 7) to illustrate this.

The consequential study (Chapter 7C) shows that the production of YOX from the recycling process of phosphorous powder causes less environmental impacts than the production from primary resources, as long as the co-produced europium enables the production of more fluorescent lamps at the expense of halogen lamps. If this represents the actual market situation, it is worthwhile to stimulate these recycling operations, for example with the help of subsidies. This is further discussed in the next section.

The attributional LCA showed that recycled YOX is accountable for impacts associated with the production and waste treatment of a fluorescent lamp. Recycled YOX is accountable for higher impacts than primary YOX related to human toxicity (non-cancer effects) (Chapter 7B). This is mainly caused by

the use of mercury in the fluorescent lamp tube. High impacts related to mercury could motivate policy makers to confine the use of mercury by legislation. However, a ban on mercury will obstruct the production of fluorescent lamps – which were found to be environmentally desirable over halogen lamps. Therefore, legislation might better focus on recycling of mercury instead of a complete ban. Besides, mandatory recycling of mercury facilitates the availability of phosphorous powder as well (Machacek et al 2015). This illustrates that attributional LCA can inform policy makers which applications might be affected by legislation (Hertwich 2014).

The results of the attributional LCA showed that the use of recycled aluminum, glass and mercury in the fluorescent lamp strongly reduces the impacts for which a lamp is accountable. Policy makers could stimulate the use of recycled materials in a closed loop. It should be emphasized that closed-loop recycling is not necessarily environmentally preferable over open-loop recycling (Geyer et al 2015). Recycled mercury could also be used in other applications where it could substitute primary mercury, for example, to make sustainable thermometers. However, we would argue that it is more advantageous to increase the sustainability of applications that have the potential to reduce environmental impacts – such as fluorescent lamps that could displace halogen lamps – than applications that do not necessarily contribute to lower environmental impacts, e.g. a thermometer. A similar suggestion was done in Section 2.3.2, with regard to the use of europium. There are several potential users of europium and the supply of europium is constrained. The consequential LCA of Chapter 7C showed that the use of europium in fluorescent lamps could lead to environmental benefits. Therefore, policy makers could use this information to stimulate the availability of europium for lamps, for example by providing subsidies to the producer of the lamps.

- Consequential LCAs inform policy makers whether a process or application is environmentally beneficial
- Attributional LCAs inform policy makers which applications are affected by legislation
- Policy makers can support environmentally beneficial processes by subsidies
- Policy makers can adapt the implementation of legislation if it affects environmentally beneficial applications or processes
- Policy makers can stimulate the use of materials of which supply is constrained in environmentally beneficial applications, in order to make these applications more sustainable

### 3.2. Policy options to stimulate environmentally beneficial behavior

Governments can implement policy measures to stimulate environmentally beneficial behavior. We could consider two types of policy measures:

- The use of LCA results to support policy-making
- The use of the LCA method to identify whether the real-life market situation supports environmentally beneficial behavior

The first type of policy measures is already shortly discussed in the previous section. In this section, we discuss whether policy measures can be applied to improve the extent to which the LCA results represent actual impacts. In the attributional and consequential methods that are described in this thesis, economic values have a large influence on the assessment of environmental impacts:

- Attributional LCA
  - Economic allocation: An economic activity exists due to the revenue it generates. Therefore, the relative revenue of a co-product represents its relative responsibility for the impacts of the co-producing activity

- Consequential LCA
  - Determining co-product: Market prices are used to identify whether a product is a determining or a dependent co-product
  - Demand constraints: The relative market price between a recycled and a primary product is used to identify whether demand constraints for the recycled product exists. If the prices are the same, there are no demand constraints and only the additional supply of recycled material leads to environmental benefits.

To identify the determining co-product in a consequential LCA, not only market prices are used but also market trends and marginal operating costs. This aspect is not further discussed in relation to policy measures. If it is uncertain which product is the determining co-product, a sensitivity analysis could be done in which the status of the products is alternated.

In all analyses, it is assumed that a company will only use a recycled material if it does not lead to financial disadvantages in comparison to a primary material. However, Kätelhön et al. (2016) show that alternative options – in their example favoring rice husk from a far region over natural gas – could be environmentally beneficial, although this is economically less interesting for the company. Some companies might, however, make suboptimal decisions to show their commitment to environmental protection (Kätelhön et al 2016). In this section, we discuss potential policy measures that could stimulate environmentally beneficial behavior, without financially disadvantaging the companies that are involved.

### 3.2.1. Avoiding economic disadvantages

First of all, it is considered that a company should not experience economic disadvantages from an environmentally beneficial decision. We use a hypothetical configuration of a recycling situation in Figure 8-4 to identify the relevant flows and actors. The numbered flows in Figure 8-4 indicate revenues or costs related to the flow. The definition of the terms in Figure 8-4 corresponds to the terms of Table 8-3. The company that produces the recycled material should not have to pay more for sending the waste to the recycling process than sending the waste to the disposal facility. If this would be the case, a subsidy ( $S$ ) could be allocated to reduce the costs for the company that provides the waste. If the company has to pay for disposal, i.e. revenues are negative:

$$E1. \quad \textcircled{4} - S \leq \textcircled{3}$$

If the company can sell the waste for a positive revenue, the revenues for selling the waste to the recycling facility should be at least equal as selling the waste to a disposal facility:

$$E2. \quad \textcircled{4} + S \geq \textcircled{3}$$

The user of the recycled material should not experience economic drawbacks either. It could be possible that due to the use of recycled material additional costs must be made, for example, if electricity use increases. This could be avoided by allocating a subsidy to the user of the material:

$$E3. \quad \textcircled{7} + \textcircled{9} - S \leq \textcircled{8}$$

The use of recycled material could also lead to a more efficient production process, e.g. the use of glass cullet in the production process of glass (GPI 2010). In that case, the economic benefits are represented by a negative value for  $\textcircled{9}$ .

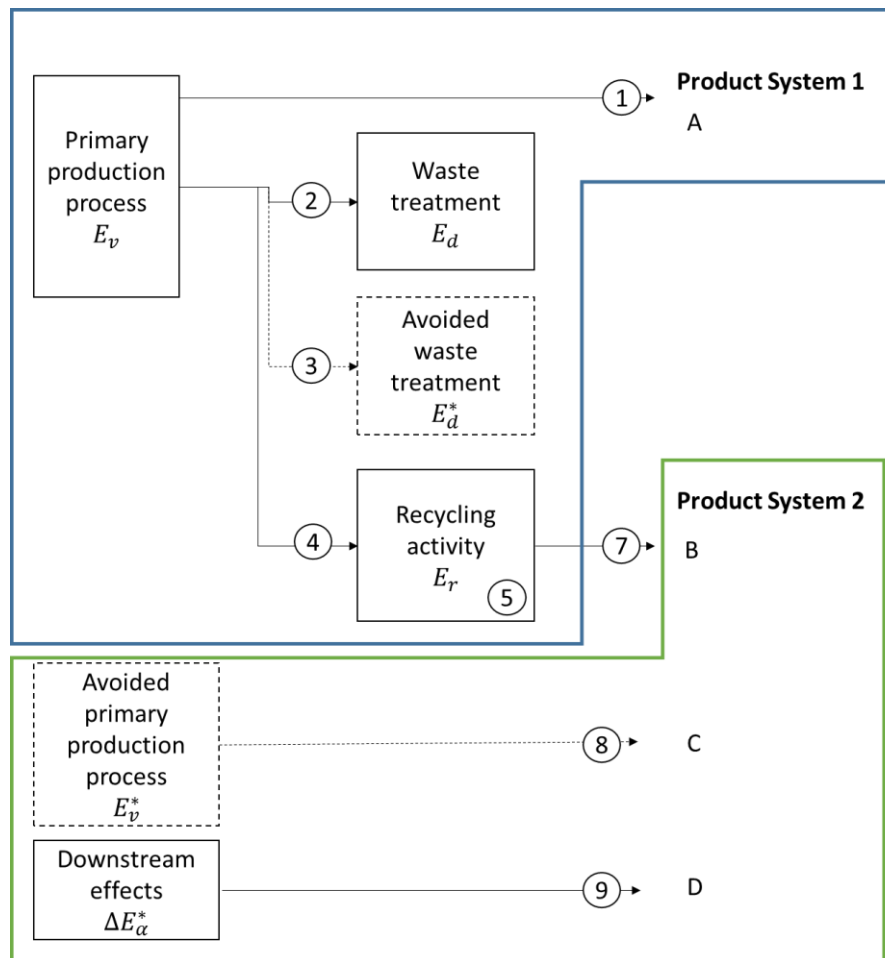


Figure 8-4 Hypothetical configuration of actors in a product system where recycling is introduced. Product System 1 delivers product A. Part of the waste of this product system is recycled into product B. Before the implementation of the recycling process, this waste was treated in an alternative disposal activity. Product B displaces the use of product C, although indirect effects take place in Product System 2 which requires the additional consumption of product D. The numbered flows represent costs or revenues due to the supply or demand of materials.

### 3.2.2. Policy measures in attributional LCA

A process-oriented attributional LCA could show whether higher or lower impacts are attributed to a recycling process in comparison to the alternative route of waste treatment and primary production. In other words, it shows which process is more sustainable. A product-oriented LCA assesses the sustainability of the whole supply chain of a product, in comparison to an alternative supply chain. Economic allocation is applied to identify the share of impacts of a co-producing process for which a product is accountable. Subsidies might be attributed to different actors in the supply chain, to influence the results of the economic allocation.

We consider that the “corrected” LCA results after applying the subsidies undermine the usefulness of the attributional LCA. In the previous sections, it was discussed how attributional LCA could inform a company on the sustainability of the company’s activities, considering potential risks related to environmental impacts upstream and downstream. If a company starts to use a recycled material, the company starts a new engagement with the supplier of the to-be-recycled waste. It is in the interest of the user of the material to be aware of impacts that take place upstream during the production of the recyclable waste. If the waste is provided by a highly impacting product system, there is a risk that the supplier of the waste will be affected by future regulations. This might lead to an increase in the production efficiency and perhaps a decreased production of the waste. It could also lead to impact-

related taxes or fines that the producer might pass to the consumer of the waste, or the product system might cease to exist altogether. Furthermore, if upstream suppliers of the product system that delivers the waste appear to be heavy polluters, this could affect the image of the company that further processes recycled waste from this product system. Therefore, subsidies might not be useful if attributional LCA is used to assess the sustainability of a product's life cycle by quantifying one's accountability for impacts.

### 3.2.3. Policy measures in consequential LCA

It was discussed before that recycling could lead to indirect effects in other product systems, which could be environmentally disadvantageous. This is better reflected in a consequential LCA, which calculates the global impacts of a change in production or consumption. The same case study of Figure 8-4 is used to show potential intervention strategies within a consequential LCA. In a consequential LCA, the impacts of a product can be calculated by the market-driven substitution method (see Chapter 6):

$$E4. \quad E_{tot} = E_{\alpha} + (1 - RC) * E_v + RC * \left( \frac{(1 - A_{RC})}{C_{RC}} * (E_{RC} - E_d^*) + A_{RC} * \frac{Q_{RC}}{Q_v} * (E_v - \Delta E_{\alpha}) \right) + (1 - RRE) * E_d + RRE * \left( (1 - A_{RRE}) * E_d + A_{RRE} * \left( E_{RRE} + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * (\Delta E_{\alpha}^* - E_v^*) \right) \right)$$

Table 8-3 Legend of terms for Equation E4

Term	Explanation	Value
$E_{tot}$	Life Cycle Inventory (LCI) attributed to one life cycle of the product under study	LCI / unit of analysis
$E_{\alpha}$	LCI due to the downstream impacts related to the use of the material in the functional unit	LCI / unit of analysis
$E_v$	LCI due to the extraction and processing of primary (virgin) material (including processing inefficiencies)	LCI / unit of analysis
$E_v^*$	LCI due to the extraction and processing of the substituted primary material in the subsequent life cycle (including processing inefficiencies)	LCI / unit of analysis
$E_d$	LCI due to the waste treatment of the product under study at the end of life	LCI / unit of analysis
$E_d^*$	LCI due to the avoided waste treatment in the previous life cycle	LCI / unit of analysis
$E_{RC}$	LCI due to the recycling process related to the recycled content (including LCI of material losses during the recycling process)	LCI / unit of input material
$E_{RRE}$	LCI due to the recycling process related to the recycled material produced at the end of life (including LCI of material losses during the recycling process)	LCI / unit of input material
$\Delta E_{\alpha}$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the	LCI / unit of displaced primary material

Term	Explanation	Value
	use of recycled material instead of primary material in the life cycle under study	
$\Delta E_{\alpha}^*$	LCI due to additional (positive) or decreased (negative) intermediate or elementary flows due to the difference in downstream effects related to the use of recycled material instead of primary material in the subsequent life cycle	LCI / unit of displaced primary material
RC	Recycled content (recycled, recovered or co-produced material input divided by the total material input)	$0 \leq \dots \leq 1$
RRE	End-of-life recycling rate (recycled or recovered material collected at the end-of-life divided by the available material after the use phase)	$0 \leq \dots \leq 1$
$C_{RC}$	Conversion efficiency of the recycling process related to the recycled content	Unit of useful output / unit of input material
$C_{RRE}$	Conversion efficiency of the recycling process related to the end-of-life recycling rate	Unit of useful output / unit of input material
$\frac{Q_{RC}}{Q_v}$	Quality-correction factor that indicates the amount of primary material that is replaced in the current life cycle by the recycled content	Unit of displaced primary material / unit of recycled material
$\frac{Q_{RRE}}{Q_v^*}$	Quality-correction factor that indicates the amount of primary material that can be replaced in the subsequent life cycle by the recycled, recovered or co-produced material	Unit of displaced primary material / unit of recycled material
$P_r$	Unitary price recycled material	€ / unit of material
$P_v$	Unitary price primary material	€ / unit of material
$Q_{\Delta}$	Quantity of additional products needed (in numerator) or displaced (in denominator) due to the difference in downstream effects related to the use of recycled material instead of primary material	Unit of material / unit of displaced primary material
$P_{\Delta}$	Unitary price of additional products needed or displaced due to the difference in downstream effects related to the use of recycled material instead of primary material	€ / unit of material
$A_{RC}$	Market-price ratio between the recycled material and the displaced primary material in the current life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RC}/Q_v)^{-1}$
$A_{RRE}$	Market-price ratio between the recycled material and the displaced primary material in the subsequent life cycle	$\frac{(P_r + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})}{(P_v + \sum_{i=1}^n Q_{\Delta_i} * P_{\Delta_i})} * (Q_{RRE}/Q_v^*)^{-1}$

A process-oriented consequential LCA on the recycling process can indicate whether the recycling process is environmentally beneficial or not. This is the case in the following situation:

$$E5. \quad RRE * \left( E_{RRE} + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * \Delta E_{\alpha}^* \right) < RRE * \left( E_d + C_{RRE} * \frac{Q_{RRE}}{Q_v^*} * E_v^* \right)$$

Equation E5 implies that the environmental impacts of the recycling process and the indirect effects due to the use of recycled material compared to the use of primary material must be lower than the impacts of the waste treatment and the primary production of a material.

In Chapter 6, the market-price ratio between the recycled material and the primary material (including the costs of indirect effects) was introduced as an indicator for demand constraints. If the demand for a material is not constrained, the consumer of the recycled material does not have to be financially stimulated to use this material; an equal price for the two materials should be sufficient to sustain the market:

$$E6. \quad \textcircled{7} + \textcircled{9} = \textcircled{8}$$

This results in a market-price ratio of  $A = 1$ :

$$E7. \quad A = (\textcircled{7} + \textcircled{9})/\textcircled{8}$$

It is possible that the market-price ratio does not actually represent demand constraints. Potential explanations and modeling recommendations for different values for the market-price ratio are given in Figure 8-5. Ideally, a value of  $A = 1$  implies that the recycled material can substitute primary material and all the possible downstream effects are already included in the market-price ratio. However, it is possible that  $A = 1$  while the market situation would be better represented by a value of  $0 < A < 1$ . Examples of this situation are represented by the green arrows in Figure 8-5. The following situations show examples of cases in which the market-price ratio does not reflect the expected environmental consequences.

1. *Stockpiles or surpluses of the recycled material exist, while the primary equivalent is still being produced.*

It is not certain that the additionally supplied recycled material will actually substitute a primary material. The value of  $A = 1$  would credit the supplier for a substitution that might not take place. Efforts of the consumer of the recycled material are required to avoid surpluses. In this case, the market-price ratio should be adapted. The market-price ratio can be corrected by lowering the market price of the recycled material. It is assumed here that the price of the recycled material is dependent on the minimum acceptable revenue for the supplier of the waste and the costs of the recycling process:

$$E8. \quad \textcircled{7} = \textcircled{4} + \textcircled{5} - S$$

This would result in an adapted market-price ratio:

$$E9. \quad A = (\textcircled{4} + \textcircled{5} - S + \textcircled{9})/\textcircled{8}$$

The ratio can be adapted until the recycled material reaches a price that guarantees a sufficient demand. As long as the market price is influenced by subsidies, the supplier of the recycled material partly models the need for additional waste treatment, and the user of the material can model a share of avoided waste treatment.

2. *Even though the recycled material and the primary material are perfect substitutes, this is not perceived as such. Therefore, the recycled material is only used in a lower market segment. There are no differences in functionality or other properties; the recycled material only suffers from a bad image.*

In this situation, the market-price ratio does not have to be adapted. The lack of demand in the market segment does not lead to increased waste treatment. However, consumers of the recycled material in higher market segments should experience benefits to overcome the barrier of the bad image. Efforts could be done to get rid of the bad image of the recycled material, for example by temporarily

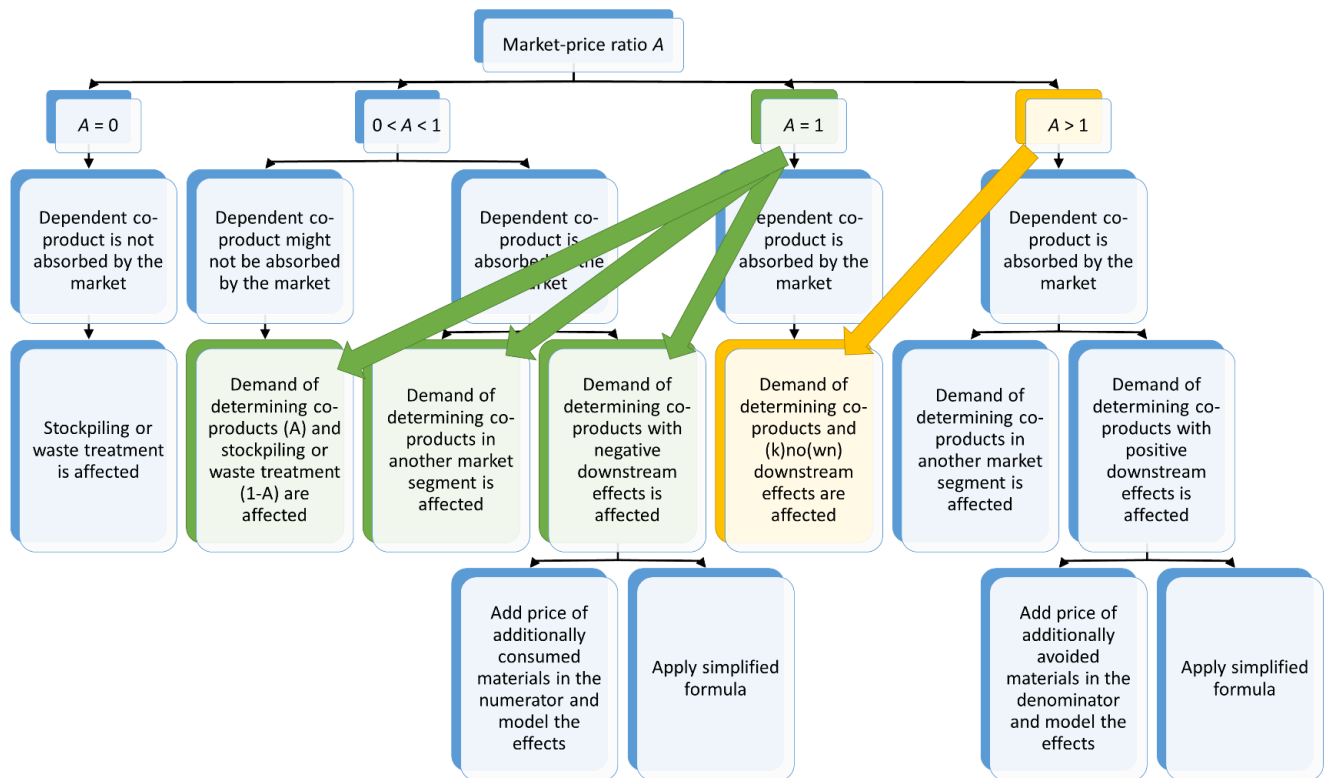


Figure 8-5 Potential situations in which the market-price ratio between the recycled and primary material does not represent the actual market situation

promoting the use of the material. This could be in the form of public procurement, marketing or rewarding consumers (financially), for example by temporary tax benefits.

3. *The user of the recycled material experiences negative downstream effects, which are not reflected by the market price.*

When negative downstream effects take place, for example, because additional processing is required if the recycled material is used or the recycled material requires more maintenance, the market-price ratio should be lowered to reflect the lack of direct comparability. The height of the subsidy should reflect the costs of the downstream effects:

$$E10. \quad (④ + ⑤ - S + ⑨) = ⑧$$

Although it does not seem intuitive to apply the subsidy upstream – e.g. to reduce ④ or ⑤, this enables to create awareness with regard to the downstream effects and the need to take these effects into account in the inventory of the life cycle. The value of  $A = 1$  is restored when all downstream costs are taken into account in the market-price ratio.

4. *The recycled material is more expensive than the primary material without providing additional downstream benefits.*

This situation, in which  $A > 1$ , is represented by the yellow arrow in Figure 8-5. In that case, the decision to use the recycled material is sub-optimal. Kätelhön et al. (2016) describe an example where the use of rice husk as an energy source is environmentally beneficial over the use of natural gas. However, the rice husk needs to be transported over a large distance, which makes the husk more expensive than natural gas. If the husk is still environmentally beneficial, taken into account the transportation



distance, subsidies could be allocated to the actor that pays for the transport (i.e. ⑤) to make the rice husk competitive. Equation E10 is also applied in this situation.

#### 5. *Consumers make irrational decisions due to high entry costs*

The case study on the fluorescent lamp in Chapter 7C showed another situation in which the market-price ratio does not entirely represent demand constraints. Fluorescent lamps are more expensive than halogen lamps, which gives an initial market-price ratio of  $A > 1$ . If positive downstream effects – such as savings on electricity use – are included, the market-price ratio becomes  $A < 1$ . It was concluded that future cost savings should be discounted to better reflect the consumer's perspective on the substitutability of two products. This example suggests that high entry costs could act as a barrier for market absorption. In this case, subsidies could be directly applied to the consumer of the product, similar as in situation 2 of this section. It is not necessary to change the market-price ratio. This ratio helps to identify the existence of downstream effects, which should be modeled in the inventory analysis.

How the subsidies should be distributed is application-specific, as multiple of the situations described above could be relevant at the same time. The suggestions that are presented in this section are not tested on real case studies, which can be interesting for further research.

If recycling is beneficial for the environment in comparison to waste treatment and producing primary materials, subsidies could be applied to:

- Correct for increased costs or reduced revenues due to the recycling process for the supplier of the waste
- Correct for a higher price related to the use of recycled material than primary material, for example due to high costs of the recycling activity or negative downstream effects
- Correct for an equal price for recycled and primary material, although the demand for recycled material is constrained
- Overcome a bad image or initial investment costs that pose a constraint on the demand for the recycled material

#### 3.2.4. *Environmental taxation*

Up to now, only policy measures in the form of subsidies have been discussed. Governmental bodies can also apply taxes to influence market interactions. Taxes can be complicated to apply due to the lack of consensus regarding the different LCA methodologies. Therefore, we would recommend to base taxes only on primary data, i.e. site-specific data, only based on elementary flows in the foreground processes. This corresponds to Scope 1 of the GHG Protocol (Greenhouse Gas Protocol 2012). The companies will be charged based on the extractions and emissions that are directly caused by the processes of the company. If a company uses intermediate products from other factories, taxes are attributed to these upstream suppliers. Suppliers could pass these taxes to their downstream users. If impacts take place downstream, consumers or waste treatment facilities will be charged for the impacts at the moment when they take place. Downstream actors can pass these taxes to their upstream suppliers by demanding lower product prices. Waste treatment facilities can pass the taxes on to companies providing the waste, by letting them pay more for their treatment service. How these taxes are divided over the different life cycle stages is related to the allocation problem in LCA: this could be based on physical relationships or reflecting the relative revenue of the products.

Governmental bodies can apply taxes based on elementary flows in the foreground subsystem. These taxes can be transferred between actors in a product's value chain.

#### 4. Conclusions

The case studies that were conducted in this thesis have provided several insights with regard to the application of allocation procedures and the interpretation of attributional and consequential LCAs. There is an ongoing discussion in the LCA community on the choice between these LCA allocation modeling approaches. This chapter discusses the choice between the approaches from an industrial perspective. A distinction is made between internal and external objectives of industrial interest. Internal objectives refer to applications within the area of influence of a company. External objectives apply to the use of LCA information that indirectly influences the operations of a company, for example by policy makers.

Both attributional and consequential LCA are found to be relevant for internal objectives of industrial interest – e.g. for product development, supply-chain management or marketing. In attributional LCA, allocation was applied with the method “allocation at the point of substitution”. However, partitioning could be avoided in a process-oriented LCA. A process-oriented LCA requires less data, while the applicability of the results is limited due to the fact that the impacts of a specific product of the process are not identified. Therefore, similar to the choice between different LCA approaches, the choice between a process-oriented and product-oriented LCA depends on the intended application and target audience. If a product-oriented LCA is required, APOS can be applied. This leads to increased data collection and the results are sometimes difficult to interpret. However, the APOS method can provide a company with information related to potential (supply) risks due to environmental impacts upstream or downstream in the product life cycle. This could represent the environmental pillar of the sustainability of the company's operations – i.e. whether the future use of a material might be compromised due to (regulations to decrease) environmental impacts. This information is not provided by the cut-off approach, although in certain situations the cut-off approach can be used to simplify the analysis. Instead of APOS, the end-of-life recycling method is often used to model recycling in attributional LCA. This (consequential) method indicates whether recycling is environmentally beneficial. However, it does not provide information on the sustainability of the use of the material.

For consequential LCA, the market-price ratio  $A$  between the recycled and the primary product was introduced as an indicator for demand constraints. Moreover, the market-price ratio can also indicate whether two products are good substitutes, or whether downstream effects take place. This type of information is also useful in an attributional LCA that compares two product systems that provide the same function.

Consequential LCA calculates whether the production of or demand for a product is environmentally beneficial. The results of a process-oriented consequential LCA can be used by a company to strengthen its reputation of being “environmentally conscious” and could support requests for financial support. The results of a product-oriented c-LCA on a recycled product could be used for marketing activities by a company that uses this product in its applications. The market-price ratio  $A$  can be used to identify which recycling activity should be promoted. The recycled content of the application should be promoted if the demand for the recycled material is generally low and the market-price ratio  $A$  is below 1, while the recyclability of the application can be emphasized if the additional supply of recycled material is environmentally beneficial and  $A > 0$ .

Furthermore, consequential LCA can give a company information related to other risks in a product's life cycle, besides environmental impacts. These are related to potential supply disruptions and the

relative position of a product to its substitutes considering the transition towards more environmentally friendly technologies. With regard to these aspects, consequential LCA has some similarities with a Resource Criticality Assessment that addresses the supply risk and the vulnerabilities to potential constraints related to the accessibility of resources, in addition to environmental impacts. Hence, the results of a consequential LCA could reflect elements of the socio-economic sustainability aspects of a company as well.

Attributional and consequential LCA are also both relevant approaches for external objectives of industrial interests, such as communication with policy makers. Consequential LCAs can inform policy makers on the products and processes that are environmentally beneficial. Results of an attributional LCA show which applications are affected by legislations of policy makers. Based on this information, policy makers can support environmentally beneficial products or processes by subsidies or an adequate tax system. Legislation could be adapted in a way that does not negatively affect environmentally beneficial products and processes. Furthermore, the supply of some materials can be constrained – such as recycled products or some primary co-products – while these materials could make an application less accountable for impacts or even environmentally beneficial. Policy makers could intervene to divert these materials towards environmentally beneficial applications, which could decrease potential risks related to environmental impacts or supply disruptions in the value chain of these applications – i.e. increase their overall sustainability, covering environmental and the above-mentioned socio-economic sustainability aspects.

The market-price ratio  $A$  in the market-driven substitution method allows supporting policy decisions to provide subsidies that stimulate the use of environmentally beneficial products or technologies. Subsidies can be attributed to suppliers of the waste, when the recycling process is costlier than the waste treatment process, or to users of the recycled material when the price for recycled material is higher than for primary products. When the market price of the recycled material does not reflect the existence of demand constraints, subsidies can be attributed to the supplier or user of the recycled material as well. Furthermore, subsidies can help companies or consumers to overcome initial investment costs that prevent the recycled material from being used. Policy measures to influence the results of an economic allocation in attributional LCA are not considered useful, as this might mask the potential risks related to upstream suppliers or downstream life cycle stages. Besides subsidies, policy-makers could apply taxes to stimulate environmentally preferable behavior. Taxes could be based on elementary flows that are measured in the foreground system. These flows are subject to least uncertainty and do not require a differentiation between attributional or consequential LCA. Taxes can be integrated into the prices of products, which can be transferred between the actors in the product life cycle.

It is concluded that both attributional and consequential LCA approaches provide useful and complementary information to companies and policy makers. The APOS method applied in this thesis reflects the environmental sustainability of a value chain, which is not represented by other methods that are often used in attributional LCA. The consequential method developed in this thesis enables to enhance an attributional study by assessing the comparability of two product systems. Furthermore, the method provides information on the environmental impacts or benefits that are caused by the use of the product, which could be applied to marketing activities. In addition, the consequential LCA provides information on elements of the socio-economic sustainability aspects of a company. Policy makers can use the results of a consequential LCA to assess the environmental performance of an activity and stimulate the demand for environmentally friendly products, which could form a basis for a greener and more circular economy.

## Chapter 9: Discussion, conclusions, and perspectives

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### 1. Introduction

In this chapter, it is first discussed whether the work of this thesis provides an adequate answer to the research question that was presented in Chapter 1. Then, the hypotheses that were formulated in Chapter 2 are tested by the findings of this thesis. A general conclusion is provided, and further research perspectives are discussed that could build forth on this current work.

### 2. Discussion

#### 2.1. A coherent approach for recycling in LCA

Over the course of this thesis we aimed to answer the following research question:

*“What is a coherent scientific approach to model recycling in Life Cycle Assessments, and how can this approach be applied to produce relevant environmental information that supports objectives of industrial interest?”*

The approach to model recycling in LCA that is proposed in this thesis is summarized in Figure 9-1. The choice for an allocation procedure is influenced by several elements of the goal and scope definition of the LCA. Archetypes of goal and scope definitions are formulated in Chapter 3 that are represented by the framework of Figure 9-1. “Allocation at the point of substitution” was identified to be the most consistent partitioning method for attributional LCA, based on a set of definitions and axioms that summarizes our perspective on the impacts for which a product system is accountable. The “market-driven substitution method” is presented as a new substitution method that allows to model the effects of avoided primary production or avoided waste treatment of materials due to additional recycling, depending on the market situation of the material. This market situation is quantified by the factor *A*: the market-price ratio between the recycled and the substituted primary material.

To determine whether this approach to model recycling in LCA provides an answer to the research question, it must be assessed whether the approach is coherent and scientific and whether it provides relevant environmental information to support objectives of industrial interest. Furthermore, it is assessed whether the approach is compliant with the standards ISO 14040 and 14044.

##### 2.1.1. The coherency of the proposed approach

The coherency of the attributional and consequential approaches in this thesis is assessed by criteria of completeness, consistency, and sensitivity. These elements are required by ISO 14044 for an evaluation procedure of an LCA study.

##### 2.1.1.1. Completeness check

A completeness check is the *“process of verifying whether information from the phases of a life cycle assessment is sufficient for reaching conclusions in accordance with the goal and scope definition”* (ISO 2006a).

Two allocation procedures are proposed in this thesis: an attributional and a consequential approach. In the systematic framework on goal-dependent modeling of Chapter 3, an extensive overview of elements is given that contribute to the choice of allocation procedure. These elements include the perspective, the reasons to conduct the LCA, the intended audience, the intended application and the functional unit. The reasons to conduct an LCA could refer to the optimization of a process or the complete life cycle of a product. Three global potential application areas of the LCA were identified: 1) quantifying environmental impacts for labeling and downstream use of the results, 2) identifying

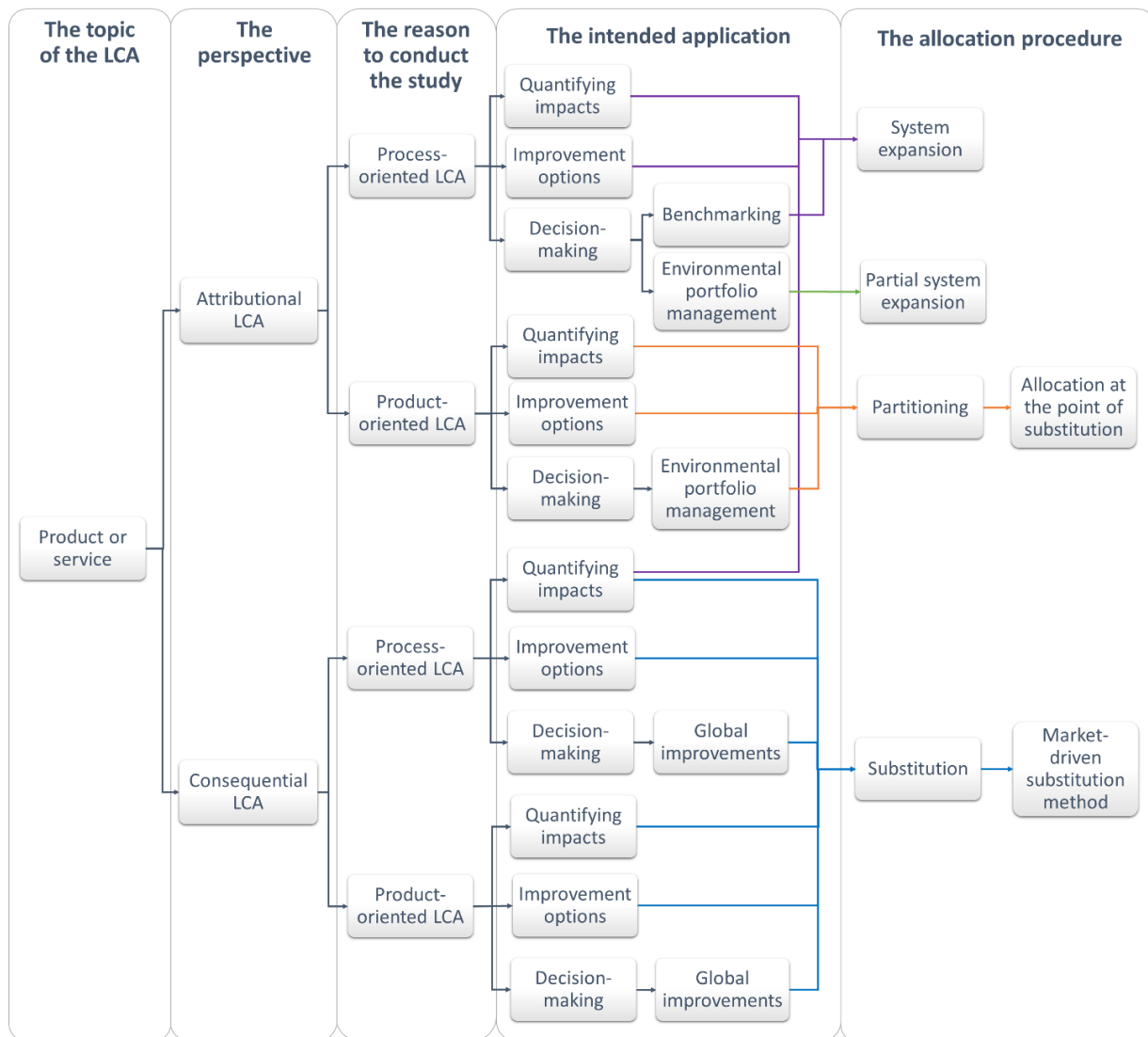


Figure 9-1 Final version of the systematic framework for consistent allocation in LCA

opportunities to improve and 3) decision-making. Decision-making could take place in multiple areas: benchmarking, environmental portfolio management or pursuing global improvements. It is our belief that these elements cover a broad range of potential LCA studies. The proposed allocation procedures enable to do a complete LCA study in line with the archetypes of LCA goal and scope definitions that are discussed in the thesis.

However, we cannot claim that the number of motivations and application areas identified in this thesis is complete. There are certainly goal and scope definitions that would require a different allocation procedure. The attributional allocation procedure “allocation at the point of substitution” is limited by the set of axioms on which the procedure is based. Other interpretations on what attributional LCA encompasses could require a different allocation procedure. Also, the consequential allocation procedure is limited by the number of mechanisms included in the analysis, as well as the scale and time horizon of the decision. Other mechanisms, such as the rebound effect, could require additional modeling or perhaps a different overall modeling approach. Besides attributional and consequential LCA, there might be other LCA approaches that represent different motivations to do an LCA. Further research could aim to identify additional elements that are relevant to the goal and scope definition and an allocation procedure that corresponds to these additional elements.

#### 2.1.1.2. Consistency check

A consistency check is the *“process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached”* (ISO 2006a).

Consistency has been a key element throughout the thesis. Consistency is strived for among different life cycle stages, such as multifunctional production and waste treatment processes. Although the thesis has been initiated by the chemistry sector, it was aimed to provide an approach that can consistently be applied to all materials and sectors. The preference of the metals sector has been taken into consideration, and an approach is developed that adapts to the market situation of the material, rather than to material properties or sector characteristics – although market situations and sector characteristics could overlap. Previous literature recommended to apply a different allocation procedure to rare earth elements, but in this thesis we demonstrated that this is not necessary. The main objective of the thesis was to develop an approach to model recycling in LCA. However, in Chapter 2 it was suggested that different multifunctionality situations do not require different allocation procedures. Therefore, co-production and energy recovery have been taken into consideration as well in the development of the methods. It appeared that it is indeed possible to find an approach that can consistently be applied to all situations. Finally, the allocation procedure must be consistent with the goal and scope definition of the LCA study. Therefore, the formulation of the goal and scope has been extensively discussed in this thesis, especially in Chapter 3. The developed allocation procedures are indeed consistent with the different elements of the goal and scope in this thesis and are by consequence limited to these goal and scope definitions.

#### 2.1.1.3. Sensitivity check

The sensitivity check is the *“process of verifying that the information obtained from a sensitivity analysis is relevant for reaching the conclusions and giving recommendations”* (ISO 2006a).

The attributional and consequential allocation procedures contain both elements that are subject to uncertainties. These elements have been discussed in Chapter 7. The main element that is shared by both LCA approaches is the use of market information in the analysis.

In the attributional case study, price ranges have been applied in the inventory analysis when prices were uncertain. An uncertainty analysis indicated that the conclusions were robust, even when these ranges were taken into consideration. In the consequential case study, the identification of the marginal supplier and marginal user of rare earth elements was highly uncertain. A sensitivity analysis has been conducted to investigate the influence of the marginal user of europium on the results. This influence was very large and the sensitivity analysis provided us with insights on environmental impacts under changing market conditions. Furthermore, a sensitivity analysis was done on different market-price ratios of recycled YOX and different recycled contents of YOX. The fact that the results were sensitive to these parameters helps us to understand the mechanisms of the procedures and to facilitate decision making in uncertain market conditions. (Projected) market prices are used in several other decision-making contexts besides LCA. Uncertainties are inherent in the modeling of consequences and effects and a full understanding of these uncertainties is essential before a decision is made.

From this evaluation, we can conclude that the approaches proposed in this thesis are coherent, although limited by the elements of the goal and scope definition that are taken into consideration.

#### 2.1.2. The scientific value of the proposed approach

Transparency and objectivity are principles that can support the scientific value of the work (The National Academies Press 2009). However, LCA is often dependent on value-based decisions. For

example, it is often stated that there is no “true” way to apply allocation. Heijungs et al. (2010) argue that this does not necessarily impede the scientific value of the methodology:

*“Science always starts with observations, phenomena, facts. But sooner or later, arbitrary elements will have to come in: the logical positivism of the Vienna circle has been abandoned by the present philosophers of science. What we define to be a mammal or a fish is a question of definition, not of facts per se. And whether we decide to label a difference between two groups as “statistically significant” depends on the arbitrarily chosen significance level. Thus, whenever we discuss a “scientific” framework for LCA, we should not be afraid of introducing arbitrary elements and values, as long as we acknowledge this [...]. The use of subjective utility functions can help to progress economics, and so can it help to progress the science of LCA.*

*On the other hand, acknowledgment of the fact that LCA, or indeed any other scientific tool or theory, contains arbitrary elements should not induce one to fall in the post-modernist trap of denying the existence of reality or objective facts. The challenge is to construct a theory and a way of working that is sufficiently science-based, but that also contains a sufficient amount of subjective and well-recognizable aspects.”*

In Chapters 5 it is discussed that the identification of “accountability for impacts” in attributional LCA is based on subjective assumptions. These assumptions have been formalized in a set of axioms on which the allocation procedure is based. These axioms are part of the scope of the LCA, which makes the allocation procedure in line with the goal and scope definition of the study. The LCA results should therefore not be used in a different LCA study that applies a different goal and scope, including different subjective assumptions on how to identify the responsibility for impacts. This is obviously a limitation of the LCA study. However, it is considered that this presentation of subjective assumptions makes the study more transparent and reproducible, which increases its scientific value.

Subjective principles are also present in consequential LCA. The LCA practitioner has a strong influence on the types of mechanisms that are included in the analysis, as well as the level of detail of the modeled effects. This is extensively discussed in Chapters 6 and 7C. A detailed description of the goal and scope of the LCA study makes these subjective choices explicit, which increases the scientific value of the study.

#### *2.1.3. The relevance of the proposed approach for objectives of industrial interest*

Solvay implemented a recycling process that enables to extract rare earth elements from the waste stream of used fluorescent lamps. These rare earth elements can be reprocessed into phosphors, such as YOX, ready to be used in new fluorescent lamps. The attributional and consequential approaches are tested on the case study of recycled YOX from used fluorescent lamps in Chapter 7.

The results of the attributional LCA show that the recycling process of YOX is accountable for lower impacts than the alternative route of waste treatment and the primary production of REEs. If a producer of REEs would produce recycled YOX at the expense of primary YOX, this company would be accountable for less environmental impacts. A potential risk factor of the recycling process are the impacts related to the treatment of the phosphorous powder. Recycling of YOX only marginally affects the impacts of a fluorescent lamp, due to the relatively low recycling rates. The impacts of a fluorescent lamp are mainly reduced by high recycled contents of glass, aluminum, and mercury. A consumer of recycled YOX engages him/herself in the value chain of the fluorescent lamp and is, therefore, accountable for upstream impacts of the fluorescent lamps. These impacts are mainly caused by the consumption of glass, mercury, aluminum, copper, and primary REEs. If the consumption of these materials is discouraged by future policies, for example by environmental taxation, this supply route of recycled YOX could be affected.



The consequential LCA shows that, under current circumstances, recycling of YOX is not only beneficial for the impacts attributed to a producer of REEs, but also for global environmental impacts. However, the results are strongly dependent on the market situation of the materials in the products and their potential substitutes. In this case study, we assumed that the demand for europium does not affect primary production routes, but the use of this element in its marginal application. As europium is mainly used in energy-efficient lamps, the marginal application was assumed to be the fluorescent lamp. The recycling process of YOX leads to an increased availability of europium on the market, which could result in the increased production of fluorescent lamps. If these lamps replace halogen lamps, large environmental gains can be achieved due to the low energy efficiency of halogen lamps. However, if fluorescent lamps compete with LED lights, the additional availability of europium could postpone the implementation of LED lamps. LED lamps are more energy-efficient than fluorescent lamps, so this can be environmentally disadvantageous.

The consequential approach shows that it is environmentally beneficial to recycle critical raw materials under the following conditions:

- The increased availability of the recycled material results in an increased use of this material by a “clean” technology, i.e. this application is the marginal user,
- Alternatives for this clean technology are more impactful, not only on the level of primary production but considering the whole product system. This includes downstream impacts related to processing, transport, use and waste treatment,
- The impacts related to the recycling process do not outweigh the benefits of using the cleaner technology.

As mentioned in Chapter 1, the recycling facility of Solvay will be shut down due to the current low prices of primary REEs. If the costs of the recycling process would be integrated into the market price of recycled YOX, recycled YOX might become more expensive than primary YOX. It is unlikely that consumers of YOX would opt for the recycled product, as this decision would be sub-optimal. This situation is described in Chapter 8. The results of the consequential LCA show that this recycling situation should be stimulated, as it is environmentally beneficial. A market situation could be created that supports the recycling activity by providing a subsidy to the company that organizes this activity, which would enable the company to accept a lower market price for recycled YOX. Alternatively, if the costs of the recycling process would be passed to the supplier of the waste powder, a subsidy could be provided to this actor to stimulate its participation to the recycling chain. The best location to allocate the subsidy is dependent on the actual money flows.

We conclude that the results of both attributional and consequential LCAs provide relevant results for industrial stakeholders. The results of the attributional LCA could be used by a company to identify impactful stages in the life cycle of products, which can put a constraint on the future viability of the production route. The results of the consequential LCA can be used to communicate the benefits of a company's processes to other stakeholders, which could support subsidy requests. Both LCA approaches could support marketing activities. This depends on the interests of the target audience. It should be emphasized that the LCA studies in this thesis are based on several simplifications and assumptions, for example with regard to the impacts of different lamps and the market situations of materials. These simplifications and other uncertainties must be taken into consideration when the results are considered for further use.

#### *2.1.4. Compliance with the requirements for allocation of ISO 14040 and 14044*

The allocation hierarchy of ISO 14044 has been presented in Chapter 2 and critically reviewed in Chapter 4. From the critical review, it appeared that multiple interpretations of the ISO hierarchy are



possible. The allocation procedures could be considered to be fully attributional, fully consequential or a mix of both approaches. This provides the freedom to conduct different types of LCA studies. However, it is also a source of inconsistencies in LCA studies or guidelines that aim to be compliant with the standard.

The compliance of the proposed allocation procedures for attributional and consequential LCA with the ISO standard is discussed in Chapters 5 and 6, respectively. System expansion – in the sense of the addition of functions to the functional unit – can technically be applied in both types of LCA. However, the usefulness of system expansion has limitations, which are discussed in Chapters 3 and 7C. Allocation cannot be avoided if it is the purpose of the LCA to identify the impacts related to the demand for a product. In consequential LCA, system expansion rarely avoids the need to model indirect consequences and has, therefore, limited use.

The multifunctionality situations discussed in this thesis are generally examples of joint production, which cannot be solved by the modeling of physical relationships. Instead, economic relationships are used as a basis for allocation in both attributional and consequential LCA. ISO 14044 states further requirements that should be considered when allocation is applied. The attributional allocation procedure “allocation at the point of substitution” is compliant with all these requirements. These additional requirements are more difficult to interpret in a consequential context, as they seem to refer to partitioning approaches and system boundaries. As system boundaries do, ideally, not exist in consequential LCA, we would argue that allocation is avoided by expanding the system boundaries to include all affected processes in the analysis. This is not the interpretation of system expansion that was initially applied in this thesis. However, the freedom of interpretation of the ISO standard enables to consider a broad range of approaches compliant with ISO 14044.

## 2.2. Hypotheses testing

In Chapter 2, three hypotheses were formulated that represent the starting point of the research of this thesis, based on the state of the art. The hypotheses are tested in this section. In other words, it is assessed whether the results of this thesis are in accordance with other scientific literature and the common practice of LCA.

Hypothesis 1: A single allocation procedure can be applied to recycled products, co-products and complex products that are involved with multiple multifunctionalities.

In this thesis, two distinct allocation procedures have been presented for attributional and consequential LCA. These allocation procedures have been represented by mathematical formulas that show the parameters and mechanisms that are relevant for the allocation procedures. For both LCA approaches, the formulas have been expressed in three ways:

- 1) A representation of a simple product containing one material. Part of this material is recycled, and part comes from primary sources. At the end of life, the product is partly recycled and partly treated as waste.
- 2) A representation of a complex product that contains different materials. Some of these materials might come from recycled sources and some might be recycled at the end of life. This formula, therefore, can contain different recycled contents and end-of-life recycling rates.
- 3) A representation of a product that contains materials that were produced as a co-product in another product system. Similarly, co-products can be produced during the different life cycle stages of the product as well.

The three different representations of the formula enable the understanding of the mechanisms from different perspectives, without influencing the actual calculations. This demonstrates that a single

allocation procedure can be applied to different types of multifunctionality situations, and Hypothesis 1 is not rejected.

It has been argued in other literature that some co-products require a different allocation procedure. In a consequential LCA, the production of co-products is modeled by the substitution of an alternative production route for this product. There are products that are exclusively produced as co-products and no single-output process for these products exists. This is the case for rare earth elements. Weidema et al. (2013) recommend applying a slightly different modeling procedure in this situation. However, the case study on rare earth elements of Chapter 7C showed that it is not necessary to apply a different allocation procedure for this type of co-production situations. Even if there is no alternative production route for a material, there is always a consumer that can reduce its demand, by switching to an alternative product or technology. It can be more difficult to find a good substitute and it is likely that downstream effects take place upon substitution, but the allocation procedure remains the same.

Hypothesis 2: The allocation procedure is dependent on the goal and scope of the LCA.

From the literature review of Chapter 3, it appeared that the goal and scope of the LCA determine which allocation procedure can be applied. Recycling can be modeled by partitioning in an attributional LCA or by substitution in a consequential LCA. The perspective of the LCA is the decisive factor in the choice between an attributional or consequential LCA. If the LCA practitioner aims to identify for what impacts the producer or user of a product can be held accountable, an attributional LCA is applied. If the LCA practitioner is interested in the global impacts that are caused by the production or use of a product, a consequential approach is applied. The main difference between these approaches lies in the philosophy that one is accountable for the choices that he or she makes or facilitates within the product's value chain. These choices can affect choices of other actors in the value chains of other products via market mechanisms. Even if the first actor is not accountable for the choices within other product value chains, these effects do contribute to global impacts.

It appeared that the allocation procedure is not only dependent on the application of an attributional or consequential approach. Other relevant elements of the goal and scope definition are the intended application of the LCA, whether the study is process or product-oriented, and the definition of the functional unit. All these aspects of the goal and scope definition contribute to the formulation of archetypical LCA goal and scope definitions, which ask for different allocation procedures. Therefore, Hypothesis 2 is not rejected in this thesis. Chapter 3 gives step-by-step guidance on how to define the goal and scope of a study and what allocation procedures could be relevant. Chapter 5 and 6 show subsequently how these procedures can be applied.

Hypothesis 3: Both attributional and consequential LCA can serve objectives of industrial interest.

The choice between attributional and consequential LCA was discussed in Chapter 2. The attributional approach is most often applied. Attributional LCA has a longer history of data collection and is often considered as less complex and easier to interpret than consequential LCA. WRI and WBCSD (2011) published a list of typical motives for industry to conduct an LCA. These motives refer to the reduction of risks related to impacting stages of a product's value chain and product differentiation. Due to the fact that attributional LCA represents impacts that are specific to the stakeholder, this approach is considered to be indeed suitable for industry goals. Also, Chapter 4 showed that most LCA guidelines that are targeted to industries recommend applying an attributional approach. However, it is important to acknowledge that decisions purely based on an attributional LCA could lead to negative consequences outside the company's perimeter.

The attributional LCA methodology can be considered in a broader sustainability analysis on the company's operations. A sustainability assessment identifies whether a current practice can be maintained in the future, considering environmental, economic and social issues. An attributional LCA can reveal potential risks due to high environmental impacts related to upstream suppliers, downstream use, or waste treatment of a product. Companies should anticipate future policy measures that make impacting value chains economically unfavorable. While attributional LCA can be applied to represent the environmental pillar of sustainability, a consequential LCA can provide a company with useful information on other aspects. Results of a consequential LCA can be used in marketing. The market-price ratio  $A$  could indicate whether the recycled content or the recyclability of a product should be promoted. This element of the consequential methodology can also be used in a process-oriented attributional LCA that applies system expansion. The market-price ratio of two products could indicate whether the two product systems are indeed comparable or whether additional processes should be added in one of the alternative systems. This would make for a more realistic benchmark.

Furthermore, a consequential analysis shows similarities with a resource criticality assessment that assesses the economic sustainability of resource use with regard to supply risks and vulnerability to supply restrictions. These elements are also considered in a consequential LCA in the form of supply constraints and the substitutability of materials. Besides, a consequential LCA provides the company with information on the relative position of their product on the market with regard to the transition towards cleaner technologies. Therefore, consequential LCA can be used as a strategic tool beyond the assessment of environmental impacts. As both attributional and consequential LCA can provide useful information for companies, Hypothesis 3 cannot be rejected.

It was shortly discussed in Chapter 8 that similar conclusions could be drawn with regard to policy makers. Consequential LCAs can inform policy makers on the environmental impacts that are caused by different products or processes. Policy makers could be motivated to stimulate the most environmentally friendly production routes. The results of attributional LCAs can indicate whether environmentally beneficial production routes are sustainable or not, for example, due to impacting stages in the value chain of a product. Legislation could be designed in order to increase the sustainability of environmentally beneficial production routes.

In Chapter 1 we discussed that recycling activities are not always economically viable. Governments could provide financial aid to stimulate environmentally beneficial activities. However, before these measures are implemented, there must be a clear indication that the recycling activity is indeed environmentally beneficial. This can be demonstrated by a consequential LCA. Consequential LCAs assess global impacts which should be the concern of public authorities – although we can also imagine situations where countries would try to minimize their accountability for impacts, for example in a global taxation system. We suggest how to apply subsidies if market prices do not reflect the ideal market situation for the recycling activity to take place in Chapter 8.

### 3. Conclusions

Recycling is a potential solution to decrease environmental impacts as well as other issues related to the use of materials. Whether recycling is indeed environmentally beneficial can be assessed with an LCA. However, modeling of recycling in LCA is an ongoing topic of discussion. This thesis had as objective to develop a coherent and scientific approach to model recycling in LCA, which produces results that are relevant for companies. To reach this objective, several sub-objectives were formulated in Chapter 1. Each of the chapters of this thesis treats one of these sub-objectives.

*Sub-objective 1: Provide an overview of the state of the art of the modeling of recycling in LCA*

Chapter 2 provides an overview of the state of the art of the modeling of recycling in LCA. Recycling – as well as co-production in general – makes a product system multifunctional. In LCA, multifunctional product systems require an allocation procedure to identify which environmental impacts are related to which co-functions of the product system. Allocation is, however, a heavily debated topic among experts working with LCA. LCA guidance documents and practitioners have diverging preferences for allocation procedures, while scientific developments suggest that the allocation procedure is dependent on the goal and scope of the LCA and the choice between an attributional and a consequential approach.

*Sub-objective 2: Develop a systematic framework of modeling procedures for recycling in LCA*

A coherent and science-based systematic framework of modeling procedures for recycling has been developed in Chapter 3. To this end, first, a more detailed state of the art was presented of allocation procedures for recycling. The allocation procedures have been expressed by mathematical formulas that demonstrate the different mechanisms of each procedure. The systematic framework shows that there is a relevant difference between process-oriented and product-oriented LCAs for the application of allocation. Partitioning is applied in a product-oriented attributional LCA, and substitution – either by the end-of-life recycling method, the waste mining method, or the 50/50 method – in a product-oriented consequential LCA. The application of partitioning and substitution can be avoided in a process-oriented LCA by the use of system expansion. Hence, the allocation procedure is dependent on different elements of the goal and scope definition of the LCA: the perspective, the reason to conduct the study, the intended application and the definition of the functional unit. Based on these elements, archetypes of LCA goal and scope definitions are formulated that represent typical LCA research questions that are supported by the framework.

*Sub-objective 3: Identify current consistency gaps and unresolved problematics with regard to the modeling of recycling in LCA*

The systematic framework that is developed in Chapter 3 is limited in the sense that it does not give guidance in *how* partitioning can be applied in an attributional LCA, and how the choice can be made between the three substitution methods for different types of materials in a consequential LCA. This choice is dependent on the market situation of the material, which could be quantified by price elasticities. The use of price elasticities is limited, due to the fact that they are difficult to calculate. They might not be available for the material under study, they can be aggregated, or referring to a different time horizon than the scope of the LCA study. Furthermore, existing literature referred to multiple recycling loops and stockpiling as missing elements that should be considered in an allocation approach.

Numerous (governmental) guidelines are available that provide specific recommendations on allocation. These guidance documents are critically reviewed in Chapter 4 with respect to the consistency of their recommendations with the systematic framework of Chapter 3. None of the guidelines is fully consistent with the framework. Partitioning is rarely proposed to model recycling in an attributional LCA. If substitution is recommended, the market situation of the material is not always taken into consideration. Only the ILCD Handbook proposes the waste mining method for recycled materials that are in low demand. Different types of LCA goal and scope definitions are often not considered and the goal and scope that are represented by the guideline are seldom described in detail. Often, different allocation procedures are recommended for different types of multifunctionality situations. Furthermore, some guidelines explicitly apply an attributional approach, while combining this with elements of a consequential LCA. The critical review showed that clear

guidance to conduct an attributional and a consequential LCA in a consistent manner is still missing. This guidance is provided in Chapters 5 and 6 of the thesis.

*Sub-objective 4: Enhance current modeling procedures to increase their consistency*

The approach of partitioning in attributional LCA has been given a scientific basis in Chapter 5 by the application of an axiomatic method. From this, “allocation at the point of substitution” with economic allocation was identified as the partitioning approach that represents best a product’s accountability for impacts. With a new equation, it is demonstrated that the partitioning approach can calculate the inventory of a product that has been recycled multiple times before while differentiating between the recycled content and the end-of-life recycling rate.

In Chapter 6, the new market-driven substitution method has been introduced for consequential LCA in which the market-price ratio  $A$  between the recycled and the substituted primary material allows to indicate whether additional recycling substitutes the production of primary products or avoids waste treatment. The market-price ratio allows operating as a switch between the end-of-life recycling method, the 50/50 method, and the waste mining method. Furthermore, the market-price ratio aids in identifying suitable substitutes and indirect downstream effects.

Furthermore, in Chapter 6 we developed a Causal Loop Diagram (CLD) that can be used as a tool to identify the indirect effects of the supply or demand of a material in a consequential LCA. This CLD includes all the effects that are calculated by the market-driven substitution method. The CLD differentiates between determining co-products – e.g. primary products – and dependent co-products, e.g. recycled products. Besides, it is considered that some primary products are only produced as dependent co-products, which are therefore modeled by the market-driven substitution as well.

Dependent co-products for which demand is low are not necessarily treated as waste. Primary dependent co-products are more likely to be stockpiled. Stockpiles are considered – together with waste streams of scraps and end-of-life products – as valuable sources of material. Therefore, anthropogenic stocks are identified as the marginal supplier of dependent co-products for which demand is constrained. The production from anthropogenic stocks is referred to as recycling or “valorization”.

*Sub-objective 5: Apply the modeling procedures to case studies of the chemical industry in order to demonstrate and test their applicability and relevance*

The formulation of archetypical LCA goal and scope definitions and the application of the systematic framework have been demonstrated by a case study on the recycling of rare earth elements from fluorescent lamps in Chapter 7. This case study allowed to illustrate the application of the allocation procedures “allocation at the point of substitution” and the market-driven substitution method. The attributional case study has shown that recycled rare earth elements are accountable for lower environmental impacts than primary rare earth elements. The consequential case study has demonstrated that recycling of rare earth elements is environmentally beneficial, as long as these elements will be used in fluorescent lamps in order to replace less energy-efficient halogen lamps.

*Sub-objective 6: Identify how the modeling procedures can provide information of industrial interest*

It was discussed in Chapter 8 that both attributional and consequential LCA provide relevant information for companies. Attributional LCA shows whether the operations of a company are environmentally sustainable. In consequential LCA, the market-price ratio  $A$  allows to indicate whether the recycled content or the recyclability of a product is environmentally beneficial. This information could be used in marketing activities. Consequential LCA furthermore shows similarities with a resource criticality assessment. Therefore, a consequential LCA could indicate whether the operations of a company are sustainable from a socio-economic point of view. Also for policy makers, attributional

and consequential LCA are relevant: Consequential LCA shows which products contribute to a more environmentally friendly society. Attributional LCA shows which products are affected by governmental policies. Regulations could be designed such that environmentally beneficial products become more sustainable. Furthermore, the market-driven substitution method can aid to identify whether subsidies could create a market situation that stimulates environmentally beneficial behavior.

#### *Overall conclusion*

The objective of this thesis was to develop a coherent and scientific approach to model recycling in LCA, which produces results that are relevant for companies. This objective has been achieved by the development of a systematic framework of allocation procedures. The choice for an allocation procedure is dependent on the goal and scope of the LCA. The procedures of the framework are further enhanced to allow for a consistent application in all multifunctionality situations of recycling, as well as co-production. The allocation procedures for recycling situations developed in this thesis are found to be coherent, based on scientific principles and provide relevant information for objectives of industrial interest. Furthermore, they are compliant with ISO 14040 and ISO 14044. The systematic framework and the allocation procedures can be applied by LCA practitioners and can serve as inspiration for future guidance documents. The main limitation of the systematic framework is the dependency of the allocation procedure on the defined archetypes of LCA goal and scope definitions.

#### **4. Perspectives**

The work in this thesis has raised several areas that would benefit from further research.

This thesis presented an attributional and consequential case study on the recycling activity of rare earth elements from fluorescent lamps. Crude assumptions were done in both LCA approaches. The LCA would greatly benefit from a more detailed analysis of the production volumes of different mines, specific life cycle inventory of these mines, more detailed market information with regard to prices and market trends of the elements, status updates on the developments of supply and demand and a parametrized model of the separation process of rare earth elements that can provide inventory data based on the composition of the REE concentrate. In this thesis, stockpiling was introduced as a relevant element in consequential life cycle inventory. It was assumed that no impacts are associated to stockpiling activities. Further research should consider the potential environmental impacts related to stockpiling.

The Causal Loop Diagram of the consequential approach represents a number of mechanisms that are generally modeled in a consequential LCA. Further research might focus on an extension of this diagram with additional mechanisms, such as rebound effects. Price elasticities would provide useful complementary information to the approach proposed in this thesis, which is mainly based on market-price ratios. More intensive cooperation with economists would be useful to develop price elasticities on the time horizon and the level of aggregation that is meaningful for LCA studies.

Due to the fact that the archetypes of LCA goal and scope definitions that are supported in this thesis are a limiting factor for the applicability of the results, further research should focus on the identification of other types of LCA goals that might require different allocation procedures. The more guidance is developed for a wide range of LCA goals and scopes, the more consistent LCA studies can become.

The attributional LCA in this thesis is based on a set of 2 definitions and 4 axioms that supports the allocation procedure “allocation at the point of substitution”. LCA practitioners and researchers that do not agree with this allocation procedure are invited to point out which axioms do not correspond to their perspective and to construct a new set of axioms. This can serve as a basis for another

allocation procedure. Building forth on the approach of this thesis, a database of axioms and corresponding allocation procedures could be developed on which consensus might exist within the LCA community. Perhaps this would lead to the introduction of new LCA approaches, besides the most often applied attributional and consequential LCA. The dichotomy of attributional and consequential LCA has already been questioned by Suh and Yang (2014). This does not have to be considered as a problematic proliferation of methodologies, as long as these approaches serve clearly defined LCA goals and scopes, and consistency is pursued within each LCA approach. The need to acknowledge different perspectives in life cycle inventory was already brought up by Frischknecht (2010). This is in line with developments in Life Cycle Impact Assessment that acknowledge the existence of different world views, such as identified by the Cultural Theory (Hertwich et al 2000; Hofstetter et al 2000; De Schryver et al 2011), which was shortly discussed in Section 5.4 of Chapter 7B.

This thesis is focused on the Life Cycle Assessment methodology, as this method was identified as the most operational eco-efficiency tool available. LCA is supported by the concept of Life Cycle Thinking, which assesses environmental problems at the level of a product's value chain (Beaulieu et al 2015). Other concepts are developed as well, that aim to consider environmental problems on the level of the global economy, such as the circular economy, or even society, e.g. sustainable development. As these concepts are not yet operationalized, this work – and LCA in general – might be able to provide a starting point for the development of tools that can measure the transition to a more circular economy and a more sustainable society.



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## Annex I: Illustrative examples of allocation procedures

### 1. Introduction

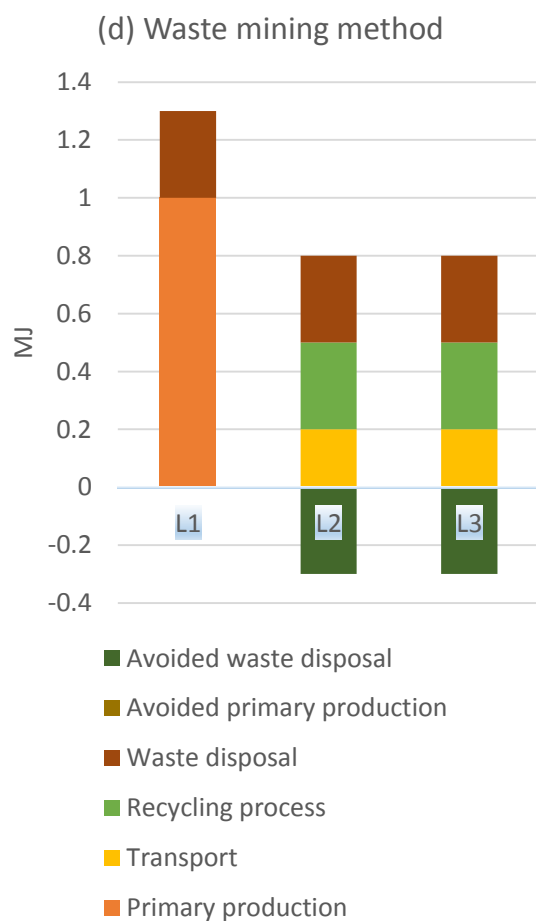
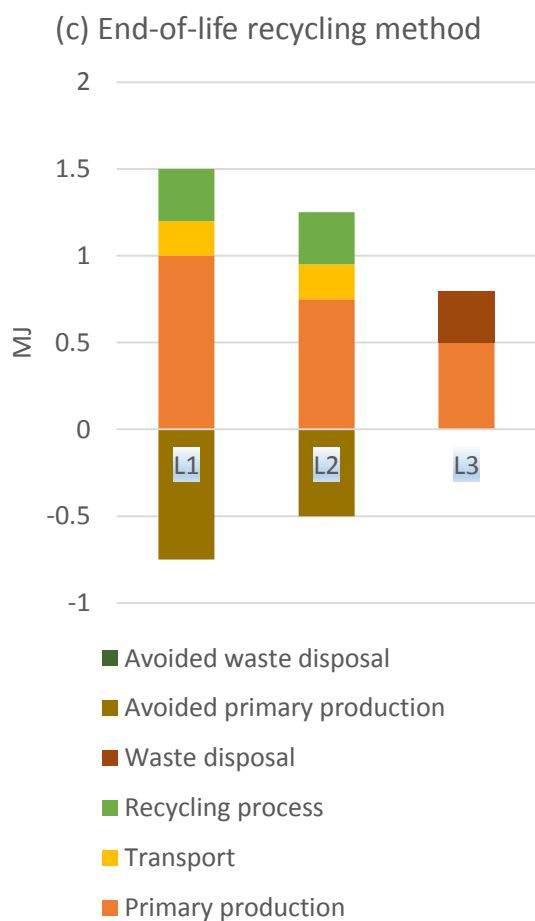
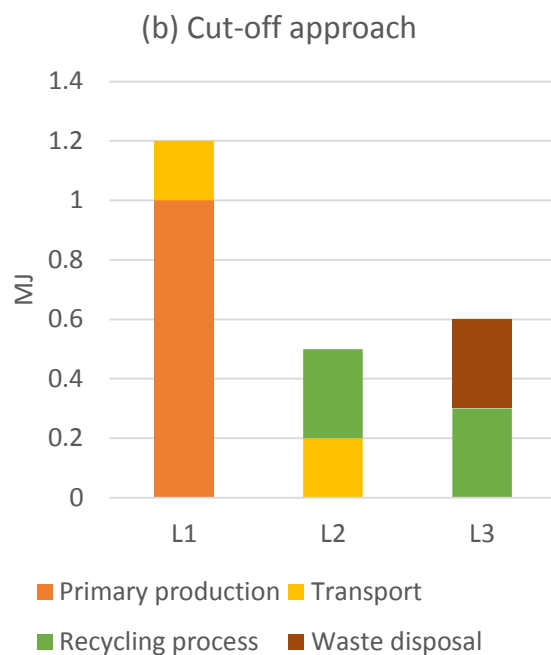
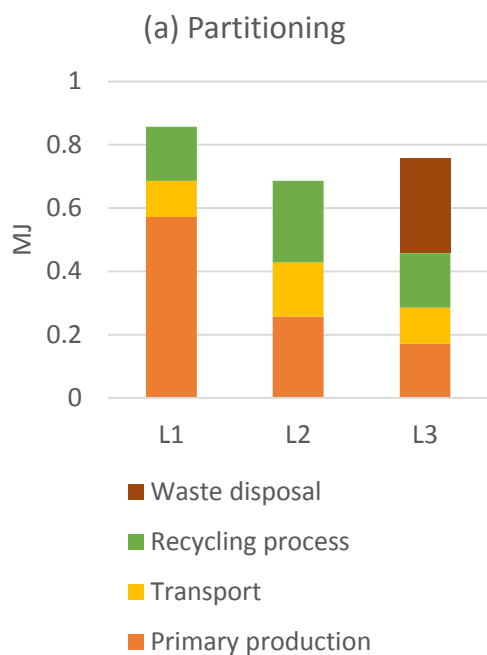
This annex provides examples to illustrate the (application of) several allocation procedures of Chapter 3.

### 2. Interpretation of recycling formulas in an open-loop recycling system

Following the example of an open-loop recycling system by Baumann & Tillman (2004) and Ekvall & Tillman (1997), we give a representation of the inventory that is calculated for each life cycle in Table I-1. In the first product life cycle (L1) only primary material ( $E_v$ ) is used. All the material is recycled at the end of life ( $RRE = 100\%$ ). The second product life cycle (L2) consumes only recycled material ( $RC = 100\%$ ) and produces the same amount of material at the end of life ( $RRE = 100\%$ ). The third product life cycle only consumes recycled material ( $RC = 100\%$ ) and sends all the material at the end of life to waste treatment ( $E_d$ ). The relative quality of the material in the respective life cycles is 1, 0.75 and 0.5. In the partitioning approach, these qualities are captured by relative economic values. Note that all the terms are multiplied with the quantity of the functional unit (e.g. mass). A graphical representation of the distribution of the processes among the life cycles according to different allocation procedures is given in by figures a-e of Figure I-1.

Table I-1 Calculation of the LCI in an open-loop recycling system per life cycle

Method	L1	L2	L3
Partitioning	$[E_v + E_{RRE}] * \frac{1}{1 + 0.75}$	$\left[ \frac{E_v + E_{RRE}}{1 + 0.75} * 0.75 + E_{RRE} \right] * \frac{0.75}{0.75 + 0.5}$	$\frac{E_v + E_{RRE} * 0.75 + E_{RRE}}{1 + 0.75} * \frac{0.75 + 0.5}{0.75 + 0.5 + E_d} * 0.5$
Cut-off approach	$E_v + E_{RRE}$	$E_{RC} + E_{RRE}$	$E_{RC} + E_d$
End-of-life recycling method	$0.25 * E_v + E_{RRE}$	$0.25 * E_v + E_{RRE}$	$0.5 * E_v + E_d$
Waste mining method	$E_v + E_d$	$E_{RC}$	$E_{RC}$
50/50 method	$0.625 * E_v + 0.5 * E_d + 0.5 * E_{RRE}$	$0.125 * E_v + 0.5 * E_{RC} + 0.5 * E_{RRE}$	$0.25 * E_v + 0.5 * E_d + 0.5 * E_{RC}$



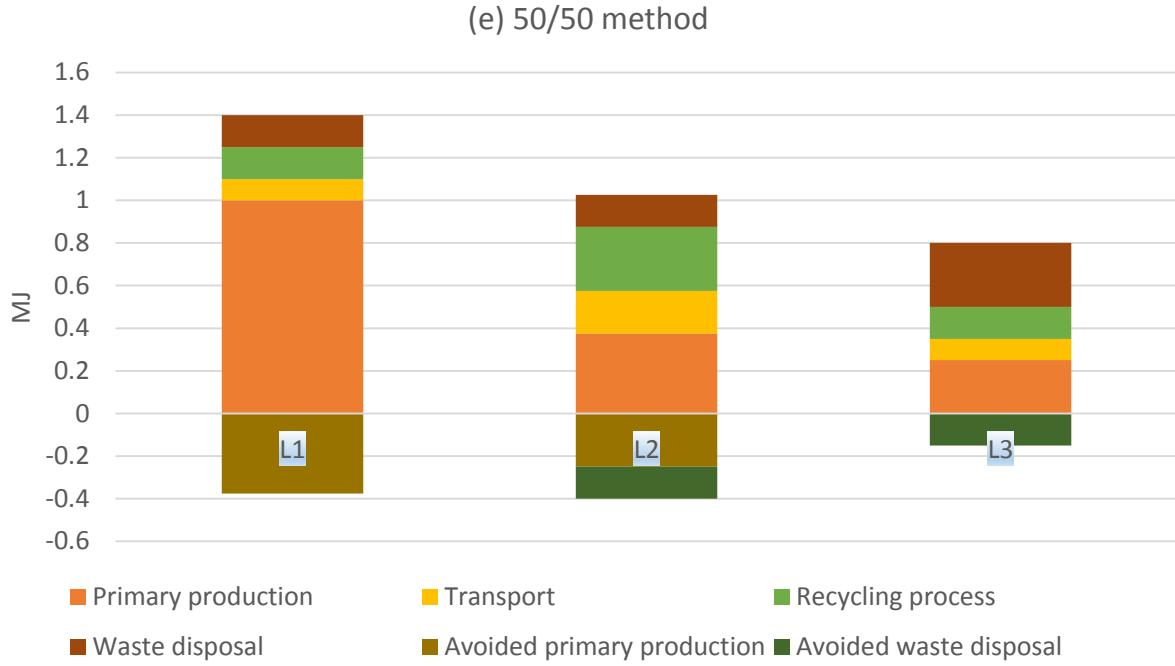


Figure I-1 Distribution of LCI due to recycling across different life cycles modeled by different allocation procedures (a-e). The 1<sup>st</sup> life cycle (L1) only produces recycled material, the 2<sup>nd</sup> life cycle (L2) consumes and produces recycled material, the 3<sup>rd</sup> life cycle (L3) only consumes recycled material. The relative quality of the material in the respective life cycles is 1, 0.75 and 0.5 (which is used for economic partitioning in the partitioning approach). The inventory values are illustrative. Negative values are inventory values that are subtracted from the life cycle under study.

### 3. Open-loop recycling maintaining the inherent properties in attributional LCA

In the partitioning method as described in Chapter 3, the inventory of the primary production, recycling impacts and waste treatment for the non-recycled fraction is shared between the primary product and the recycled product. Therefore, the user of the recycled material must model a share of these processes in the second life cycle. The inventory of each life cycle of the recycled product is calculated as follows:

$$E1. \quad E_{tot} = [E_v + E_d - RC * (E_v - E_{tot(n-1)} * F_{n-1}) - RRE * (E_d - E_{RRE})] * 1 / (1 + RRE * C_{RRE} * F)$$

We will illustrate this formula with an example on 1 kg of aluminum. We could assume that at the end-of-life, 90% of the aluminum is recycled ( $RRE = 0.9$ ), with a conversion efficiency of aluminum waste to ready-to-use aluminum of 100% ( $C_{RRE} = 1$ ). The recycled aluminum has the same market price as primary aluminum ( $F = 1$ ). The inventory for the first life cycle (where only recycled material is produced, and not consumed) is calculated as follows:

$$E2. \quad E_{tot} = [E_v + E_d - 0 * (E_v - E_{tot(n-1)} * F_{n-1}) - 0.9 * (E_d - E_{RRE})] * 1 / (1 + 0.9)$$

Resulting in

$$E3. \quad E_{tot} = [E_v + 0.1 * E_d + 0.9 * E_{RRE}] * 1 / (1 + 0.9)$$

In the second life cycle, some of the recycled aluminum that was produced in the first life cycle is used. However, the recycled content is only 50% (which means that the remaining recycled aluminum is used in another product system). At the end of life, the aluminum is again recycled with an end-of-life recycling rate of 90%. The inventory of the second life cycle is calculated as follows:

$$E4. \quad E_{tot} = [E_v + E_d - 0.5 * (E_v - [E_v + 0.1 * E_d + 0.9 * E_{RRE}] * 1/(1 + 0.9)) - 0.9 * (E_d - E_{RRE})] * 1/(1 + 0.9)$$

Note that the term in blue is identical to the inventory attributed to the first life cycle of the aluminum. This can be repeated for the third life cycle:

$$E5. \quad E_{tot} = [E_v + E_d - 0.5 * (E_v - [E_v + E_d - 0.5 * (E_v - [E_v + 0.1 * E_d + 0.9 * E_{RRE}] * 1/(1 + 0.9)) - 0.9 * (E_d - E_{RRE})] * 1/(1 + 0.9)) - 0.9 * (E_d - E_{RRE})] * 1/(1 + 0.9)$$

Again, the colored terms refer to the inventory attributed to the previous life cycle. The total inventory per life cycle is calculated as represented in Table I-2.

Table I-2 Total inventory per life cycle considering multiple recycling loops

Life cycle	Inventory
1 <sup>st</sup>	$0.53 * E_v + 0.05 * E_d + 0.47 * E_{RRE}$
2 <sup>nd</sup>	$0.40 * E_v + 0.07 * E_d + 0.60 * E_{RRE}$
3 <sup>rd</sup>	$0.37 * E_v + 0.07 * E_d + 0.63 * E_{RRE}$
4 <sup>th</sup>	$0.36 * E_v + 0.07 * E_d + 0.64 * E_{RRE}$

This can continue until the  $(n+1)^{th}$  life cycle, where  $n$  is the number of recycling loops (i.e. for the first life cycle  $n = 0$ ). The formula to calculate the inventory after  $n$  recycling loops is as follows:

$$E6. \quad E_{tot}(n) = b * (a - RC * E_v) * \frac{1 - (b * RC * F)^n}{1 - b * RC * F} + a * b^{n+1} * RC^n * F^n$$

- $a = E_v + (1 - RRE) * E_d + RRE * E_{RRE}$
- $b = \frac{1}{1 + RRE * C_{RRE} * F}$

Figure I-2 shows that the inventory values converge to a number, which can be calculated by:

$$E7. \quad \lim_{n \rightarrow \infty} E_{tot}(n) = b * (a - RC * E_v) / (1 - b * RC * F)$$

Note that this formula is relevant if a material can be recycled without loss of inherent properties.  $E_v$ ,  $E_d$  and  $E_{RRE}$  are assumed to be similar in the product system under study and in the rest of the material market. For  $RC$  and  $RRE$  average values in the material market could be assumed. It is not necessary to assume that  $RC$  and  $RRE$  are equal, as it would be in case of actual closed-loop recycling, which is not a realistic assumption for most materials.

If aluminum is used that has been used 6 times before, Equation E6 can be used to calculate the inventory that is attributed to the life cycle that has delivered the consumed aluminum (for  $n = 5$ ). This value can be filled in for  $E_{tot(n-1)}$  in Equation E1. Equation E1 calculates the impact of the life cycle under study, based on the end-of-life recycling rate of the life cycle under study.

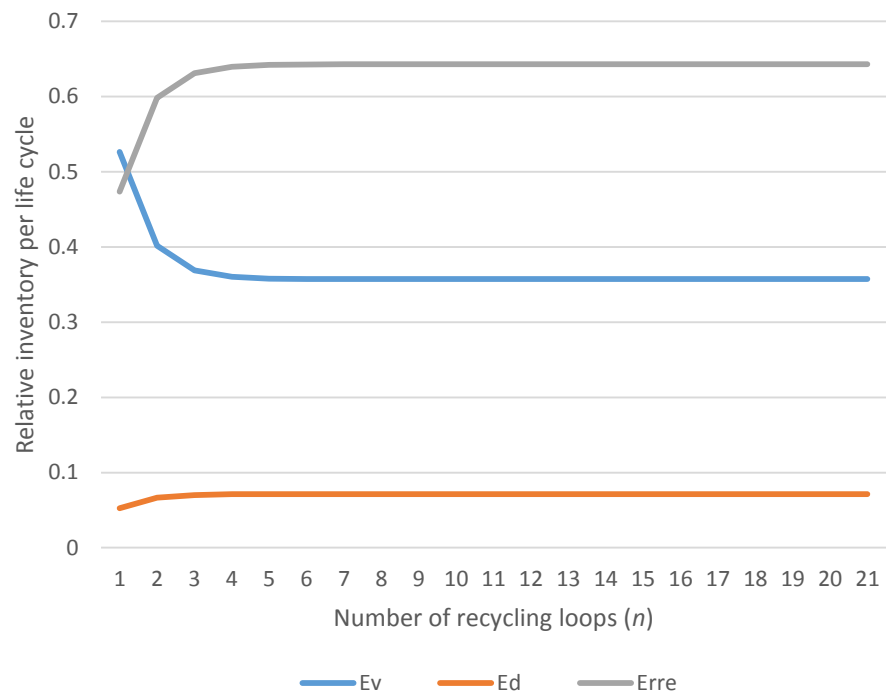


Figure I-2 Inventory per life cycle after n recycling loops





# Annex II: Additional analyses on the attributional case study of Chapter 7B

## 1. Introduction

This annex provides additional information to the attributional case study of the recycling of rare earth elements from fluorescent lamps (Chapter 7B). A discussion is given on economic partitioning of rare earth elements and the results of an uncertainty analysis are provided.

## 2. Economic partitioning of REEs

Rare earth elements are a typical example in which allocation based on physical properties is difficult to apply. If partitioning is based on physical properties, we should be able to identify a physical property that all elements have in common, such as mass. However, each element provides a different function in a different application. The usefulness of the elements in these applications is not (only) determined by their mass. Therefore, mass is not a relevant physical property to base allocation on. We consider that the relative usefulness of a material might be captured by their economic value, which is also a property that all elements have in common. Hence, their relative economic value is considered as a proxy for the relative usefulness of the material. The choice between mass allocation and economic allocation has a large influence on the impacts that are attributed to the elements (Figure II-3). In the LCA in this chapter, it was aimed to identify the responsibility for impacts of a product. If mass allocation is applied, it is tacitly assumed that a product is responsible for impacts due to its mass. In that case, cerium would be most responsible for the impacts of the mining process. However, in this chapter (and in Chapter 5) the perspective was applied that an economic activity exists due to the expected revenues of the activity. Then, a product is responsible for impacts due to its (economic) value. From this perspective, neodymium is considered responsible for the largest share of impacts of the mining process. As neodymium is a critical element in high demand, and a surplus of cerium currently exists, it is considered that economic allocation provides results that reflect best the responsibility for impacts of the mining process.

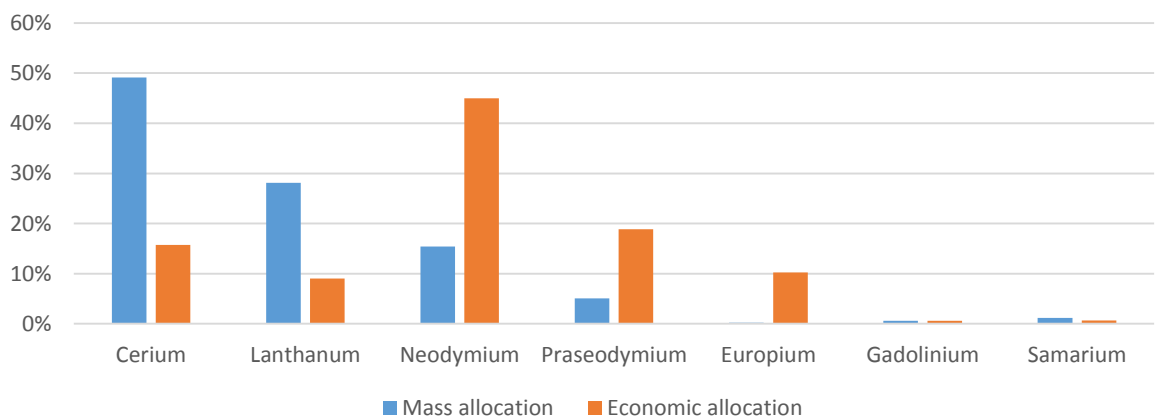


Figure II-3 Distribution of inventory among the rare earth elements extracted from bastnäs site based on mass and revenue

### 3. Uncertainty analysis

Where possible, data ranges have been used in the inventory analysis instead of data points. This enables us to do an uncertainty analysis in Simapro. This uncertainty analysis is based on a Monte Carlo simulation

with 10000 repetitions. The result of this analysis is shown in Figure II-4. From this we can conclude that the probability that recycled YOX has a lower impact than primary YOX is very high for most impact categories, except for water resource depletion, ionizing radiation and human toxicity.

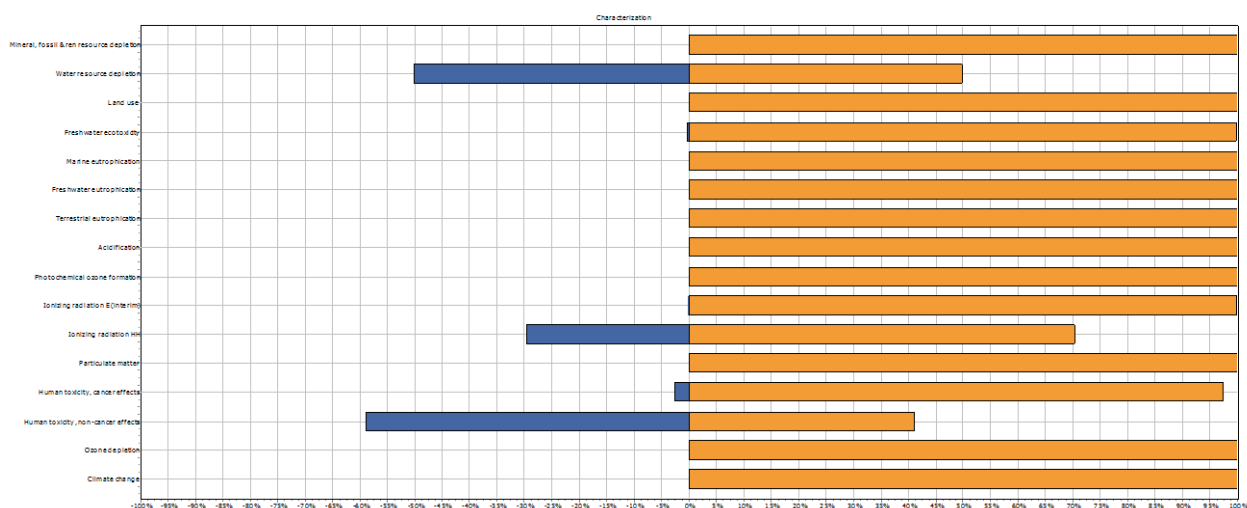


Figure II-4 Uncertainty analysis that shows the probability that recycled YOX has a lower (yellow) or higher (blue) impact than primary YOX. Confidence interval: 95%

## Annex III: Additional analyses on the consequential case study of Chapter 7C

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### 1. Introduction

This annex provides background information to the consequential case study on the recycling of rare earth elements of Chapter 7C. The annex shows which data is used to calculate the determining co-products of primary deposits of rare earth elements (REEs). Furthermore, a sensitivity analysis is presented that shows the influence of the market situation of fluorescent lamps on the results of the LCA.

### 2. Market information REEs

Table III-3 summarizes the market information on which the calculation of the determining co-product is based.

Table III-3 Market information of REEs

REE	Market prices 2013 (USD/kg) <sup>a</sup>	Market trend <sup>b</sup>
Lanthanum	7.866	6%
Cerium	7.863	6%
Praseodymium	91.4	6%
Neodymium	71.8	7%
Samarium	13.3	10%
Europium	1095	8%
Gadolinium	24	9%
Terbium	920	8%
Dysprosium	555	9%
Holmium	66	8%
Erbium	68	6%
Thulium*	53	8%
Ytterbium	53	8%
Lutetium	1201	8%
Yttrium	26	8%

<sup>a</sup>(Statista 2016a)

<sup>b</sup>(European Commission 2014a)

\*Assumption: same market price as ytterbium, as both are co-products from the same extraction activity

### 3. REE characteristics of deposits

Table III-4 - Table III-10 show the characteristics of the deposits in which REEs can be produced as a determining co-product. Based on these characteristics, the determining co-product of each mine is calculated.

Table III-4 Characteristics of the Mountain Pass deposit

Mountain Pass, US	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	0.1	0.03	80.0
Lanthanum	33.2	2.61	0.2
Cerium	49.1	3.86	0.1
Praseodymium	4.34	3.97	1.4
Neodymium	12	8.62	0.6
Samarium	0.8	0.11	12.5
Europium	0.1	1.10	80.0
Gadolinium	0.2	0.05	45.0
Terbium	trace		
Dysprosium	trace		
Holmium	trace		
Erbium	trace		
Thulium	trace		
Ytterbium	trace		
Lutetium	trace		

<sup>a</sup>(USGS 2015)

Table III-5 Characteristics of the Xunwu deposit

Xunwu, Jiangxi, China	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	8	2.1	1.0
Lanthanum	43.4	3.4	0.1
Cerium	2.4	0.2	2.5
Praseodymium	9	8.2	0.7
Neodymium	31.7	22.8	0.2
Samarium	3.9	0.5	2.6
Europium	0.5	5.5	16.0
Gadolinium	3	0.7	3.0
Terbium	trace		
Dysprosium	trace		
Holmium	trace		
Erbium	trace		
Thulium	trace		
Ytterbium	0.3	0.2	26.7
Lutetium	0.1	1.2	80.0

<sup>a</sup>(USGS 2015)

Table III-6 Characteristics of the Longnan deposit

Longnan, Jiangxi, China	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	65	16.90	0.12
Lanthanum	1.82	0.14	3.02
Cerium	0.4	0.03	15.00
Praseodymium	0.7	0.64	8.57
Neodymium	3	2.15	2.33
Samarium	2.8	0.37	3.57
Europium	0.1	1.10	80.00
Gadolinium	6.9	1.66	1.30
Terbium	1.3	11.96	6.15
Dysprosium	6.7	37.19	1.34
Holmium	1.6	1.06	5.00
Erbium	4.9	3.33	1.22
Thulium	0.7	0.37	11.43
Ytterbium	2.5	1.33	3.20
Lutetium	0.4	4.80	20.00

<sup>a</sup>(USGS 2015)

Table III-7 Characteristics of the Southeast Guangdong deposit

Southeast Guangdong, China	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	59.3	15.42	0.1
Lanthanum	1.2	0.09	4.6
Cerium	3	0.24	2.0
Praseodymium	0.6	0.55	10.0
Neodymium	3.5	2.51	2.0
Samarium	2.2	0.29	4.5
Europium	0.2	2.19	40.0
Gadolinium	5	1.20	1.8
Terbium	1.2	11.04	6.7
Dysprosium	9.1	50.51	1.0
Holmium	2.6	1.72	3.1
Erbium	5.6	3.81	1.1
Thulium	1.3	0.69	6.2
Ytterbium	6	3.18	1.3
Lutetium	1.8	21.62	4.4

<sup>a</sup>(USGS 2015)

Table III-8 Characteristics of the Yangibana deposit

Yangibana, Australia	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Neodymium	76%	54.9	0.09
Praseodymium	20%	18.4	0.30
Europium	2%	22.7	3.86
Dysprosium	1%	7.4	6.77

<sup>a</sup>(Mining Technology 2016)

Table III-9 Characteristics of the John Galt deposit

John Galt, Australia	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	66.77	17.36	0.12
Lanthanum	0.46	0.04	11.96
Cerium			
Praseodymium			
Neodymium			
Samarium	1.25	0.17	8.00
Europium	0.4	4.38	20.00
Gadolinium	4.57	1.10	1.97
Terbium	1.18	10.86	6.78
Dysprosium	9.34	51.84	0.96
Erbium	7.12	4.84	0.84
Ytterbium	5.8	3.07	1.38
Holmium	3.12	2.06	2.56
Thulium			
Lutetium			

<sup>a</sup>(Northern Minerals 2011)<sup>b</sup>Based on lanthanum<sup>c</sup>Based on holmium

Table III-10 Characteristics of the Mount Weld deposit

Mount Weld, Australia	Concentration (%) <sup>a</sup>	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	trace		
Lanthanum	26	2.05	0.2
Cerium	51	4.01	0.1
Praseodymium	4	3.66	1.5
Neodymium	15	10.77	0.5
Samarium	1.8	0.24	5.6
Europium	0.4	4.38	20.0
Gadolinium	1	0.24	9.0
Terbium	0.1	0.92	80.0
Dysprosium	0.2	1.11	45.0
Holmium	0.1	0.07	80.0
Erbium	0.2	0.14	30.0
Thulium	trace		
Ytterbium	0.1	0.05	80.0
Lutetium	trace		

<sup>a</sup>(USGS 2015)

#### 4. Sensitivity analysis on the market mix of lamps

The market situation of the lamps appears to be very relevant in the calculation of the impacts of the recycling process. In 2010, the market share of LED lights in the residential market was only 1% (Holland et al 2014). Figure III-5 suggests that, at the moment, halogen lamps are still relevant competitors for fluorescent lamps, although LED lights have a rapidly increasing market share. Navigant Consulting (2012) forecasts that halogen lamps will be marginalized in residential lighting around the year of 2030, which would make the fluorescent lamps compete mainly with LED lights (Figure III-6). Currently, the adoption of LED lights in the market is inhibited by the high purchase price (European Commission 2014a; Holland et al 2014). Subsidies on LED lamps could accelerate the penetration in the market and make the recycling of fluorescent lamps economically and environmentally disadvantageous at an earlier stage. However, it should be emphasized that only the difference in electricity use during the use phase between the lamps has been considered in this LCA study. LED lamps contain more materials than fluorescent lamps, among which critical and precious metals, and would benefit from a recycling infrastructure as well (Lim et al 2013).

A sensitivity analysis is done to determine the moment when the recycling process stops to be environmentally beneficial. The primary production process of YOX starts to cause environmental impacts in all impact categories when the contribution of LED lights in the consumption mix of LED and halogen lamps that compete with fluorescent lamps is lower than 97,5% (Figure III-7). The recycling process for YOX becomes environmentally beneficial considering most impact categories when the contribution of LED is below 80% (Figure III-8). The recycling process remains impactful with regard to ozone depletion, ionizing radiation, land use and mineral, fossil and renewable resource depletion. The impacts on resource depletion increase with a higher displacement of halogen lamps, due to the fact that the Swiss electricity mix has a beneficial effect on this impact category in the ecoinvent system model. In the dataset of the Swiss electricity market, copper and lead are used in the transmission network. During the extraction of these materials, co-products are produced, such as silver and zinc. This co-production avoids the production of these latter materials from other mines where these products are the determining co-product. Therefore, the use of copper and lead has a beneficial effect on mineral, fossil and renewable resource depletion.

The impacts of the recycling route are directly compared to the impacts of the primary production route in Figure III-9. The recycling route causes less impacts than the primary production route when the contribution of LED lamps in the consumption mix is lower than 92%, except regarding ionizing radiation.



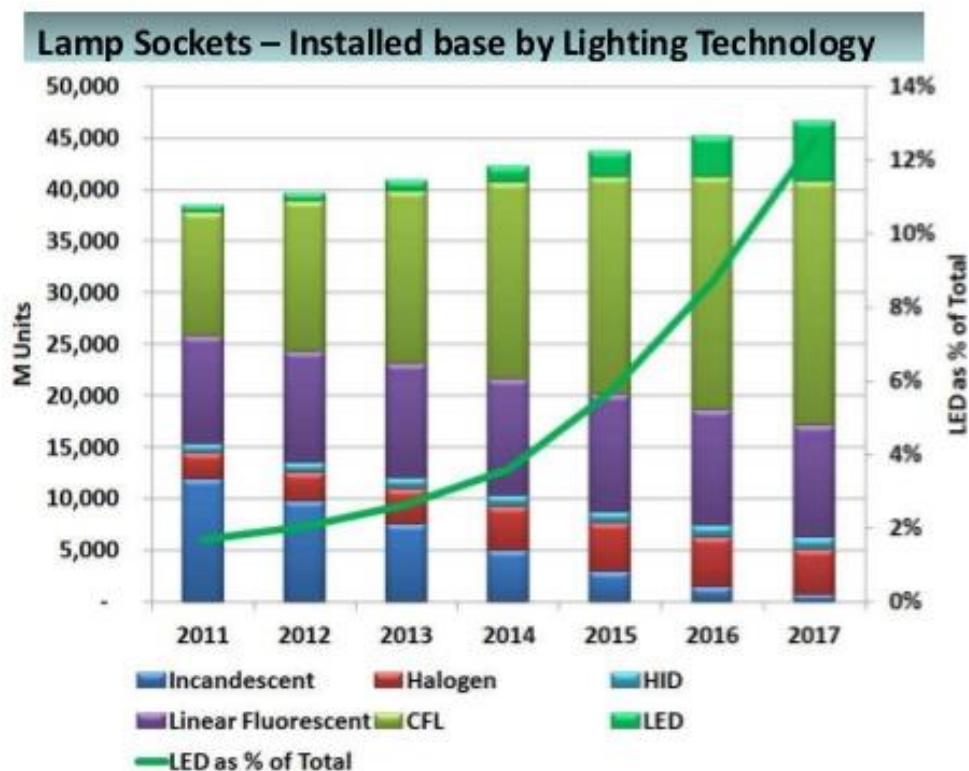


Figure III-5 Global lightning market (ON Semiconductor 2013)

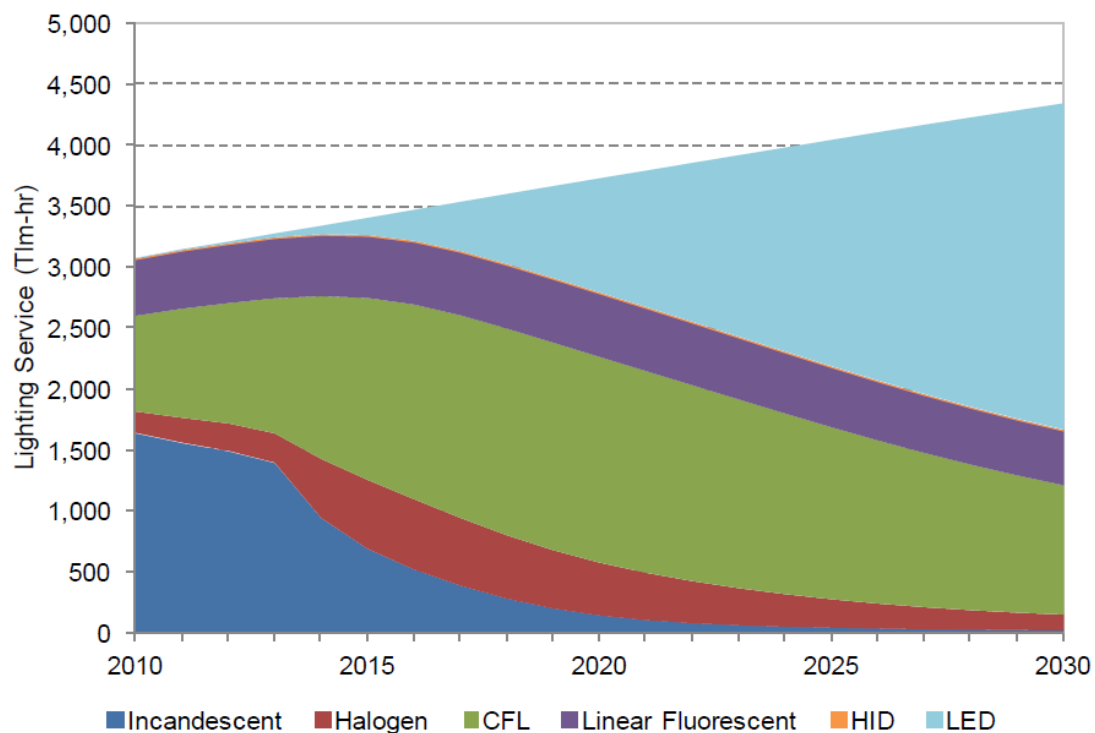


Figure III-6 Residential lighting service forecast, 2010 to 2030 (Navigant Consulting 2012)

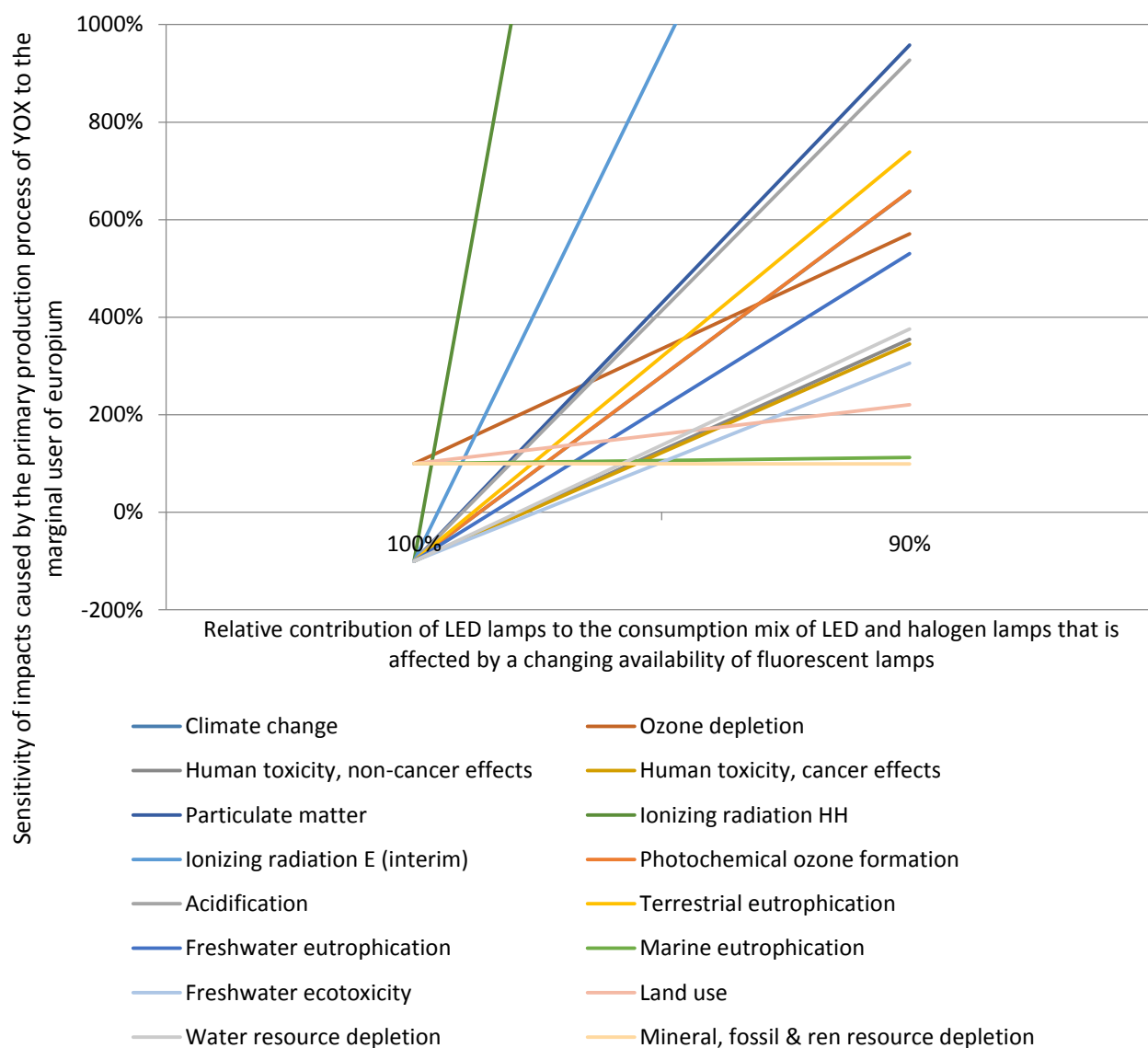


Figure III-7 Sensitivity of impact results of the primary production process of YOX to a changing contribution of LED lights in the consumption mix of lamps competing with fluorescent lamps. The contribution of LED to this mix is reduced from 100% to 90%. A value below zero indicates a beneficial effect on the environment

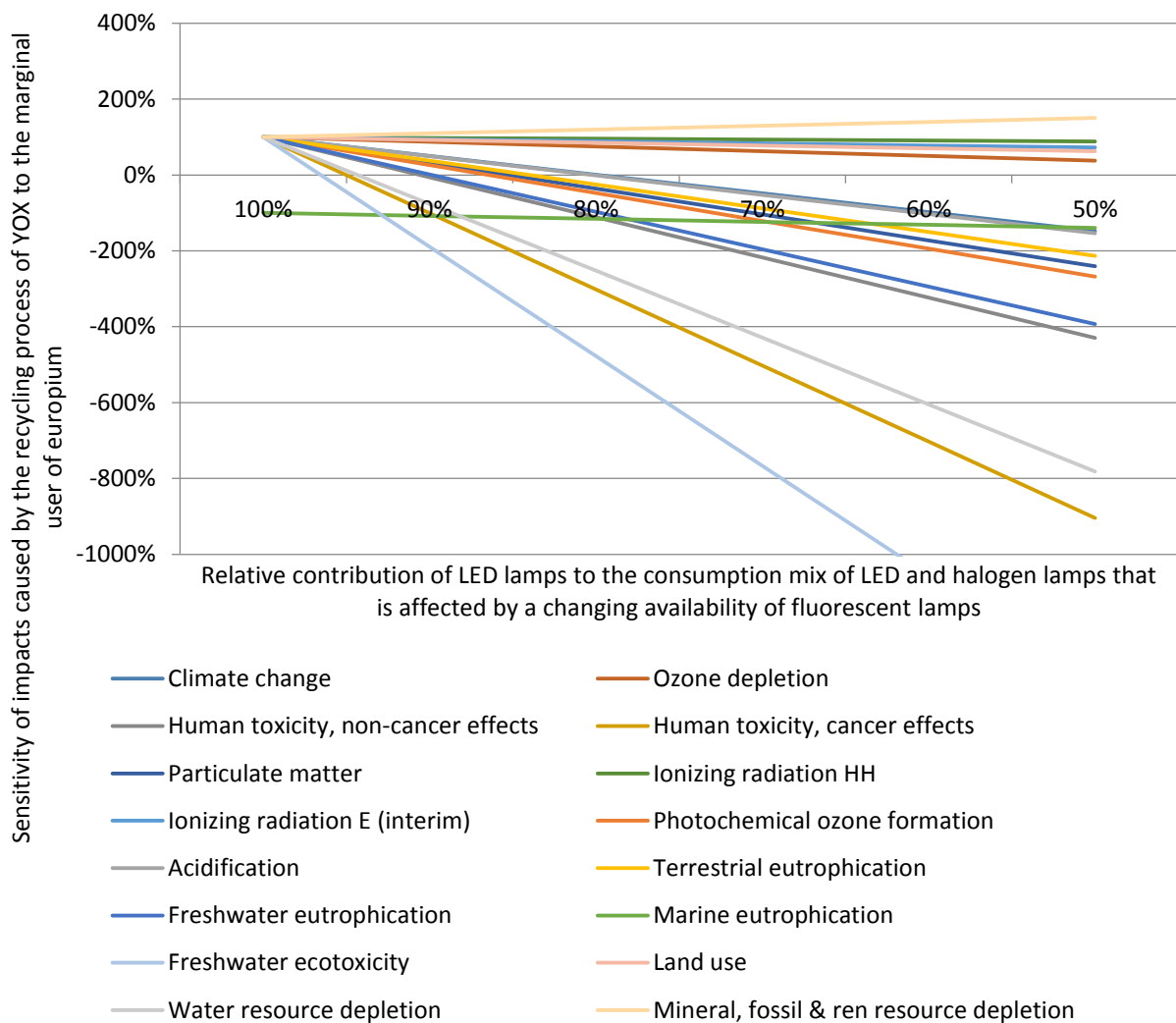


Figure III-8 Sensitivity of impact results of the recycling process of YOX to a changing contribution of LED lights in the consumption mix of lamps competing with fluorescent lamps. The contribution of LED to this mix is reduced from 100% to 50%. A value below zero indicates a beneficial effect on the environment

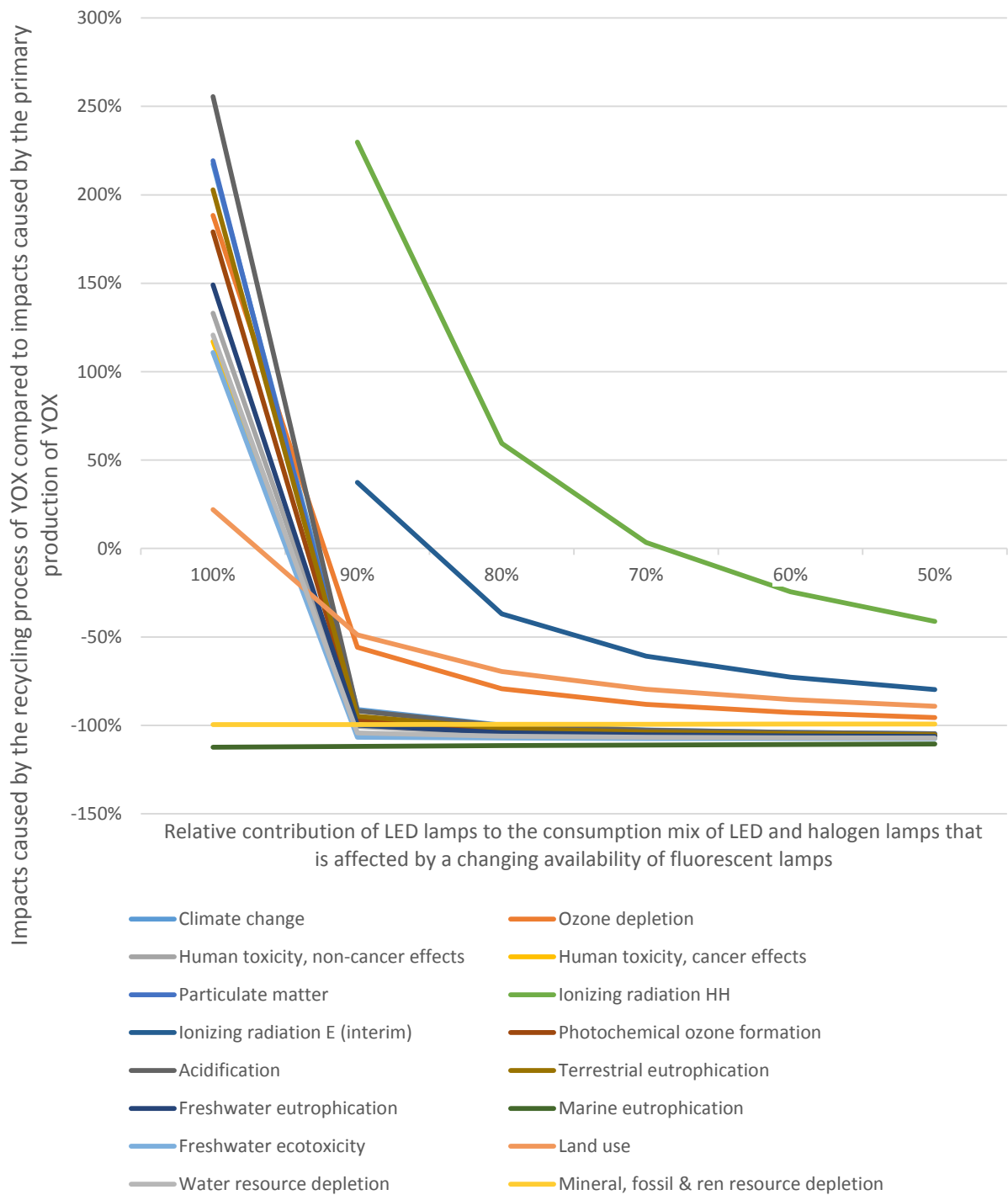


Figure III-9 Relative difference between impacts caused by the recycling process of YOX compared to impacts caused by the primary production of YOX for a changing contribution of LED lamps to the consumption mix of LED and halogen lamps that is affected by a changing availability of fluorescent lamps. The contribution of LED to this mix is reduced from 100% to 50%. A difference of zero indicates that the recycling process causes the same impacts as the primary production process of YOX. A value below zero indicates that the recycling process has a lower impact than the primary production process. Some very large values are omitted to make the figure clearer. A complete overview of the values is given in Table III-11

Table III-11 Complete overview of the values corresponding to Figure III-9

Contribution of LED to the consumption mix of LED and halogen lamps	100%	90%	80%	70%	60%	50%
Climate change	217%	-91%	-100%	-103%	-104%	-105%
Ozone depletion	188%	-56%	-79%	-88%	-93%	-96%
Human toxicity, non-cancer effects	133%	-101%	-105%	-106%	-106%	-107%
Human toxicity, cancer effects	117%	-105%	-106%	-107%	-107%	-107%
Particulate matter	219%	-96%	-102%	-104%	-105%	-106%
Ionizing radiation HH	18753%	230%	60%	3%	-24%	-41%
Ionizing radiation E (interim)	2991%	37%	-37%	-61%	-73%	-80%
Photochemical ozone formation	179%	-97%	-103%	-104%	-105%	-106%
Acidification	256%	-92%	-100%	-103%	-104%	-105%
Terrestrial eutrophication	203%	-95%	-102%	-104%	-105%	-105%
Freshwater eutrophication	149%	-100%	-104%	-105%	-106%	-106%
Marine eutrophication	-112%	-112%	-111%	-111%	-111%	-111%
Freshwater ecotoxicity	111%	-107%	-107%	-107%	-107%	-108%
Land use	22%	-49%	-70%	-80%	-85%	-89%
Water resource depletion	121%	-104%	-106%	-107%	-107%	-107%
Mineral, fossil & ren resource depletion	-100%	-99%	-99%	-99%	-99%	-99%

## List of publications and contributions to conferences

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The author of this thesis has published parts of the work in the following papers:

- Frischknecht, R., Benetto, E., Dandres, T., Heijungs, R., Roux, C., Schrijvers, D., ... Tschuemperlin, L. (2017). LCA and decision making: when and how to use consequential LCA; 62nd LCA forum, Swiss Federal Institute of Technology, Zürich, 9 September 2016. *The International Journal of Life Cycle Assessment*, 22, 296–301. doi:10.1007/s11367-016-1248-9 – *Resulted from the 62<sup>nd</sup> LCD Discussion Forum*
- Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Developing a systematic framework for consistent allocation in LCA. *International Journal of Life Cycle Assessment*. doi:10.1007/s11367-016-1063-3 – *Based on Chapter 3*
- Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. *The International Journal of Life Cycle Assessment*, 21(7), 994–1008. doi:10.1007/s11367-016-1069-x – *Based on Chapter 4*

The following papers were published outside the scope of this thesis :

- Vigon, B., Sonnemann, G., Asselin, A., Schrijvers, D., Ciroth, A., Chen, S. S., ... Milà i Canals, L. (2016). Review of LCA datasets in three emerging economies: a summary of learnings. *The International Journal of Life Cycle Assessment*. doi:10.1007/s11367-016-1198-2
- Schrijvers, D. L., Leroux, F., Verney, V., & Patel, M. K. (2014). Ex-ante life cycle assessment of polymer nanocomposites using organo-modified layered double hydroxides for potential application in agricultural films. *Green Chemistry*, 16(12), 4969–4984. doi:10.1039/C4GC00830H

The work has furthermore resulted in a platform presentation at the following conferences (presenting author underlined):

- *The versatility of attributional LCA – a case study on recycling of Rare Earth Elements.* Schrijvers, Dieuwertje; Lartigue-Peyrou, Françoise; Sonnemann, Guido. SETAC Europe 27th Annual Meeting (Brussels, Belgium, May 2017)
- *Towards consistent allocation procedures for co-production and recycling in LCA standards and guidelines.* Schrijvers, Dieuwertje; Loubet, Philippe; Sonnemann, Guido. 12<sup>th</sup> Biennial International Conference on Ecobalance (Kyoto, Japan, October 2016)
- *Identifying indirect effects of primary production and recycling of rare earth elements in consequential LCA.* Schrijvers, Dieuwertje; Loubet, Philippe; Sonnemann, Guido. 22<sup>nd</sup> SETAC Europe LCA Case Study Symposium (Montpellier, France, September 2016)
- *Modelling the production and recycling of rare earth elements in consequential LCA.* Schrijvers, Dieuwertje; Loubet, Philippe; Sonnemann, Guido. 62<sup>nd</sup> LCA Discussion Forum - LCA and decision making: when and how to use consequential LCA? (Zurich, Switzerland, September 2016);
- *Multiple recycling loops in attributional LCA - Misconceptions and solutions.* Schrijvers, Dieuwertje; Loubet, Philippe; Sonnemann, Guido. SETAC Europe 26th Annual Meeting (Nantes, France, May 2016)
- *Allocation formula for recycling and co-production in all product sectors.* Schrijvers, Dieuwertje; Sonnemann, Guido. 7th annual Life Cycle Management Conference (Bordeaux, France, August 2015)

The author has presented the work of the thesis by the following poster presentations:

- *Allocation for co-production and recycling in company-led LCA studies.* Schrijvers, Dieuwertje; Sonnemann, Guido. 7th annual Life-Cycle Management Conference (Bordeaux, France, August 2015)
- *Consistent allocation for co-production and recycling in LCA – A critical review of guidelines.* Schrijvers, Dieuwertje; Loubet, Philippe; Sonnemann, Guido. SETAC Europe 25th Annual Meeting (Barcelona, Spain, May 2015)
- *Market-price based substitution for short-term consequential LCA.* Schrijvers, Dieuwertje; Sonnemann, Guido. SETAC Europe 25th Annual Meeting (Barcelona, Spain, May 2015)
- *Recycling models for different sectors in LCA – Practices in the industrial sectors.* Schrijvers, Dieuwertje; Sonnemann, Guido. avniR Life Cycle in Practice Conference (Lilles, France, November 2014)

Furthermore, the following papers are in preparation:

- Schrijvers D.L., Sonnemann G. (2017) An axiomatic method for allocation in attributional LCA. *Based on Chapters 5 and 7B*
- Schrijvers D.L., Sonnemann G. (2017) Anthropogenic stocks in consequential Life Cycle Inventory - a case study on rare earth elements. *Based on Chapters 6 and 7C*

### 1. Introduction

Le changement climatique et une forte dépendance à l'égard des ressources fossiles sont considérés comme des problèmes importants de notre économie actuelle. La transition vers des technologies éco-énergétiques induit une dépendance de plus en plus grande vis-à-vis d'autres ressources comme les terres rares. Ces éléments sont utilisés dans les éoliennes, les voitures électriques et les lampes fluorescentes. L'extraction primaire de ces matériaux provoque de grands impacts environnementaux. Le recyclage est souvent considéré comme une solution pour réduire les impacts environnementaux ; non seulement dans le secteur des métaux, mais aussi pour d'autres groupes de produits : matières plastiques, verre, papier, etc. Cependant, les processus de recyclage peuvent également avoir des répercussions sur l'environnement. Il faut éviter que les charges environnementales passent d'une étape du cycle d'un produit à une autre. Ainsi, la lutte contre le changement climatique ne devrait pas avoir d'effets néfastes sur d'autres problèmes environnementaux. L'analyse du cycle de vie (ACV) est un outil utile pour évaluer les impacts environnementaux d'un produit, en tenant compte de toutes les étapes du cycle de vie et d'un large éventail d'impacts environnementaux.

Le recyclage introduit une dimension multifonctionnelle au cycle de vie d'un produit : un matériau peut être utilisé dans de multiples cycles de vie. Une allocation doit être appliquée pour identifier les impacts environnementaux du cycle de vie d'un produit. La modélisation du recyclage - et l'allocation en général - est un sujet fortement débattu dans le domaine de l'ACV. Certaines indications sont données dans la norme ISO 14044, bien qu'il soit souvent considéré que cette norme ne tient pas compte des différents objectifs de l'ACV. Différentes procédures d'allocation pourraient être nécessaires lorsque l'objectif de l'ACV est de calculer pour quel impact un produit est *responsable* ou lorsque l'ACV vise à calculer les impacts *causés* par la demande d'un produit. Ces différents objectifs nécessitent une ACV attributionnelle ou conséquentielle, respectivement. De nombreuses directives officielles ont été élaborées par des institutions (intergouvernementales), et leurs recommandations sur l'allocation sont très divergentes. En outre, ces recommandations sont critiquées par les secteurs industriels. On prétend souvent que le recyclage des métaux nécessite une procédure d'allocation différente que le recyclage des matériaux avec une situation de marché différente, comme les plastiques. Cependant, différents types de matériaux pourraient être utilisés pour des applications similaires. Les entreprises de secteurs de matériaux concurrents utilisent l'ACV pour choisir entre différents fournisseurs et à des fins de marketing. Par conséquent, une approche cohérente devrait être développée pour la modélisation des impacts environnementaux dans des secteurs et pour des objectifs d'ACV différents.

### Objectif

L'objectif d'étude de cette thèse est de développer une approche cohérente et scientifique pour la modélisation du recyclage dans l'ACV afin de produire des résultats pertinents pour les entreprises.

### Sous-objectifs

Les sous-objectifs suivants servent à atteindre l'objectif principal de la thèse :

1. Fournir un état de l'art de la modélisation du recyclage dans l'ACV.
2. Élaborer un cadre systématique de procédures de modélisation pour le recyclage dans l'ACV.
3. Identifier les manques de cohérence actuels et les problèmes non résolus en ce qui concerne la modélisation du recyclage dans les ACV.
4. Améliorer les procédures de modélisation actuelles pour augmenter leur cohérence.



5. Appliquer les procédures de modélisation aux études de cas de l'industrie chimique afin de démontrer et de tester leur applicabilité et leur pertinence.
6. Identifier comment les procédures de modélisation peuvent fournir des informations d'intérêt industriel.

## 2. Sous-objectif 1 : Fournir un état de l'art de la modélisation du recyclage dans l'ACV

### 2.1. Le recyclage est un problème de multifonctionnalité dans l'ACV

Les quatre phases de l'ACV - la définition de l'objectif et du champ d'étude, l'analyse de l'inventaire, l'évaluation de l'impact et l'interprétation des résultats - sont introduites au Chapitre 2. En outre, les études de cas de l'entreprise chimique Solvay qui sont évaluées dans la thèse sont présentées : 1) Le recyclage des éléments des terres rares (ETR) des lampes fluorescentes, 2) l'utilisation de « nouveaux scraps » dans la production du polyamide 6 et 3) le recyclage du PVC à partir des câbles électriques en fin de vie.

La formulation de l'unité fonctionnelle nécessite que le système de produit étudié soit monofonctionnel. Cependant, la plupart des systèmes de produits, en réalité, fournissent de multiples fonctions, en raison de la coproduction, du traitement combiné des déchets ou du recyclage. Si l'ACV vise à identifier l'impact d'une seule fonction, une procédure d'allocation doit être appliquée. L'introduction à l'étude de cas sur le recyclage des ETR des lampes fluorescentes montre que les problèmes multifonctionnels de la coproduction, du traitement combiné des déchets et du recyclage sont étroitement liés. Dans la littérature, il a été suggéré que l'application de différentes procédures d'allocation à différentes situations multifonctionnelles est incohérente.

Certaines directives sont fournies par l'ISO 14044 pour appliquer l'allocation. Cependant, l'ISO 14040 et 14044 ne font pas référence à des développements récents dans le domaine de l'ACV, tels que l'existence d'approches attributionnelle et conséquentielle de l'ACV. Une ACV peut être menée pour identifier les responsables des impacts d'un produit - qui nécessite une approche attributionnelle – ou pour identifier les impacts causés par la demande supplémentaire d'un produit. Ce dernier objectif de l'ACV est servi par une approche conséquentielle. La hiérarchie d'allocation de l'ISO n'est également pas applicable dans ces différentes approches. Plusieurs documents directifs (gouvernementaux) ont été développés pour fournir des recommandations plus concrètes sur la façon d'appliquer l'allocation. Cependant, ces documents fournissent des recommandations divergentes et rencontrent de nombreuses critiques, par exemple dans des secteurs industriels spécifiques. Cela indique qu'il n'existe actuellement aucun consensus sur la façon dont l'allocation devrait être appliquée, correspondant à l'objectif de l'étude de chaque ACV. Au lieu de cela, la procédure d'allocation appliquée est souvent influencée par les préférences du praticien ACV.

Les objectifs industriels typiques suggèrent que les industries s'intéressent au côté durable de leurs opérations. Une ACV environnementale peut fournir des informations sur la durabilité d'un produit ou d'un processus en ce qui concerne les risques potentiels liés aux impacts environnementaux. À cette fin, une ACV attributionnelle peut être utile, car cette approche ACV montre quels impacts environnementaux peuvent être associés à un produit ou à un processus. Les ACV attributionnelles sont en outre plus largement appliquées que les ACV conséquentielles. Cependant, le secteur de métaux est favorable à une procédure d'allocation qui peut être liée à une approche conséquentielle. Cela suggère que les ACV conséquentielles peuvent également fournir des informations qui intéressent les entreprises.

## 2.2. L'état de l'art des procédures d'allocation dans l'ACV

Au Chapitre 2, la modélisation du recyclage dans l'ACV a été identifiée comme un problème d'allocation. Le Chapitre 3 visait à identifier une procédure d'allocation cohérente pour le recyclage dans des situations divergentes.

L'état de l'art des procédures d'allocation qui peuvent être appliquées à différents types de situations multifonctionnelles est fourni. Les développements de l'ACV attributionnelle et conséquentielle dans le domaine scientifique sont pris en compte et les procédures d'allocation sont classées en conséquence. Chaque procédure d'allocation est exprimée sous la forme d'une équation mathématique. Cela permet d'identifier les différences dans les mécanismes des procédures.

On constate qu'il existe une différence pertinente entre les ACV axées sur les processus et les produits. Une ACV axée sur les processus vise à évaluer la performance environnementale d'un processus, tandis qu'une ACV axée sur les produits vise à identifier l'impact environnemental d'un produit. Les données de ce dernier peuvent être utilisées comme données de base dans d'autres études d'ACV.

Dans une ACV attributionnelle axée sur les produits, l'allocation est appliquée par une approche d'imputation. À partir de la formule d'imputation, une nouvelle équation est dérivée pour calculer l'impact d'un produit qui a été recyclé plusieurs fois auparavant. Cela démontre que de multiples boucles de recyclage influent sur les impacts d'un produit dans une ACV attributionnelle. La formule permet une différenciation entre le contenu recyclé et le taux de recyclage en fin de vie, qui n'a pas été considéré dans d'autres méthodes qui considèrent les boucles multiples. L'approche de coupure (*the cut-off approach*) est considérée comme un cas particulier d'imputation où 100% des impacts sont attribués au matériau primaire et 0% au matériau recyclé.

Dans une ACV conséquentielle, les effets du recyclage supplémentaire sont modélisés par substitution. On identifie trois méthodes de substitution qui modélisent les effets du recyclage :

- Dans la méthode de recyclage en fin de vie (*the end-of-life recycling method*), l'approvisionnement supplémentaire en matières recyclées peut éviter la production d'un matériau primaire dans le cycle de vie suivant. La demande supplémentaire de matériaux recyclés est modélisée par l'apport supplémentaire de matériaux primaires.
- Dans la méthode d'exploitation minière urbaine (*the waste mining method*), la demande supplémentaire d'un produit recyclé conduit à un recyclage supplémentaire et évite que ce produit soit traité comme un déchet. L'approvisionnement additionnel en matières recyclées est modélisé par un traitement supplémentaire des déchets.
- Dans la méthode 50/50, la consommation de matériaux recyclés évite, en partie, le traitement des déchets et entraîne, en partie, une production accrue de matières premières. L'offre supplémentaire en matériaux recyclés évite, en partie, la production de matières premières dans le cycle de vie suivant et entraîne, en partie, un traitement supplémentaire des déchets. La méthode 50/50, par conséquent, modélise la moyenne de la méthode de recyclage en fin de vie et de la méthode d'exploitation minière urbaine.

Le choix entre les trois méthodes de substitution est basé sur la situation du marché des matériaux recyclés:

- Un approvisionnement entièrement inélastique en matériaux recyclés demande la méthode de recyclage en fin de vie. Cette méthode pourrait bien refléter la situation du marché de plusieurs métaux de base.
- La méthode d'exploitation minière urbaine est utilisée lorsque la demande de matériaux recyclés est entièrement inélastique.

- La méthode 50/50 représente la situation dans laquelle l'offre et la demande du produit recyclé sont également élastiques. Cette méthode est parfois associée à la situation du marché des matières plastiques.

L'expansion du système peut éviter l'approche d'imputation dans une ACV attributionnelle axée sur les processus en ajoutant "le traitement des [déchets entrants]" et "la production de [coproduit sortant]" à l'unité fonctionnelle initiale. L'expansion du système peut également éviter de modéliser les effets du recyclage dans une ACV conséquentielle. Cependant, ces effets sont souvent pertinents en raison du fait que les effets indirects pourraient compenser les impacts ou les avantages directs, ce qui rend l'utilité de l'expansion du système limitée dans une ACV conséquentielle. Alors que l'extension du système peut être appliquée dans l'ACV attributionnelle, l'approche de substitution n'est pas toujours perçue comme correcte, car elle se produit au fil du temps et ne relève donc pas de l'instantané fourni par les ACV attributionnelles.

### 3. Sous-objectif 2 : Élaborer un cadre systématique de procédures de modélisation pour le recyclage dans l'ACV

Un cadre systématique est élaboré qui résume les résultats du chapitre 3 et relie les procédures d'allocation à une approche attributionnelle ou conséquentielle et à une perspective axée sur les processus ou axée sur les produits (Figure 1). En outre, il est considéré dans ce cadre que les ACV attributionnelle et conséquentielle peuvent servir à différents domaines d'application : quantifier les impacts, identifier les possibilités d'amélioration et permettre la prise de décision.

A partir de ce cadre, on constate que trois éléments de l'objectif de l'ACV influent directement sur la pertinence d'une procédure d'allocation :

La perspective de l'ACV : que calcule l'ACV ?

- La responsabilité des impacts
- Les conséquences sur les impacts mondiaux

La raison de l'étude :

- Évaluer la performance environnementale d'un processus de production, de valorisation ou de traitement
- Identifier les impacts liés à la demande d'un produit

L'unité fonctionnelle :

- Une fonction spécifique est évaluée
- Des fonctions multiples sont prises en compte

À partir de ces éléments, les archétypes de l'objectif d'ACV sont formulés (Table 1). Les procédures d'allocation qui sont incluses dans le cadre systématique sont appliquées à ces archétypes d'ACV. D'autre part, l'identification des procédures d'allocation pertinentes est limitée par ces archétypes d'objectif.

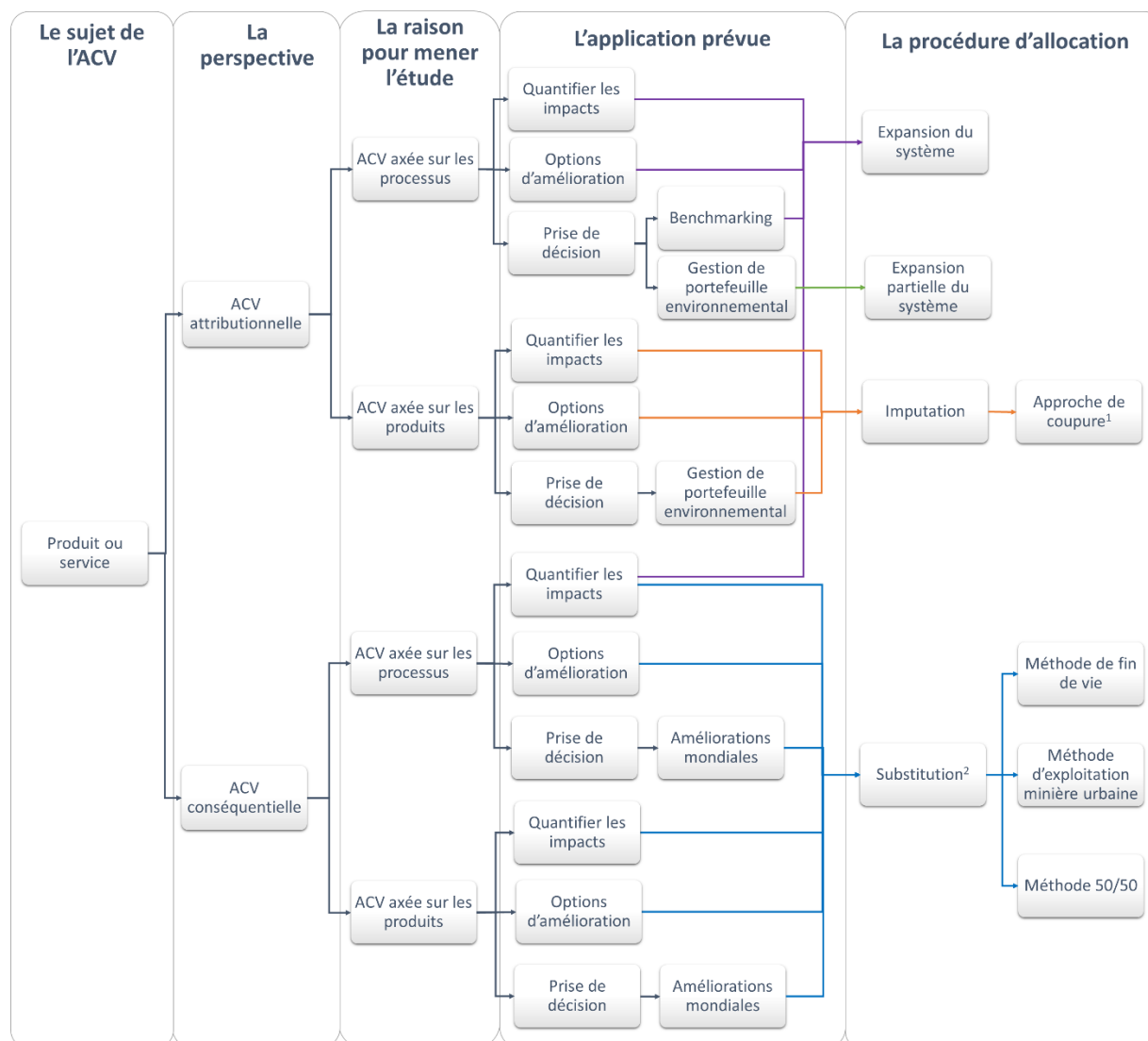


Figure 1 Cadre systématique pour une allocation cohérente dans l'ACV. <sup>1</sup>L'approche de coupure est considérée comme un cas particulier où 100% des impacts sont attribués au produit primaire. <sup>2</sup>La situation du marché de la matière indique quelle méthode de substitution est appliquée

Table 1 Blocs de construction d'archétypes d'objectifs de l'ACV. Les termes représentés par  $\alpha$ ,  $\beta$  et  $\gamma$  sont utilisés dans les archétypes d'objectifs définis dans le tableau ci-dessous

Éléments de la définition des objectifs d'ACV	L'approche ACV		Blocs de construction des archétypes d'objectifs d'ACV
La perspective de l'ACV	ACV attributionnelle	$\alpha$	$\alpha$ : La responsabilité des impacts
	ACV conséquentielle		$\alpha$ : Les conséquences sur les impacts mondiaux
La raison de mener l'étude	ACV axée sur les processus	$\beta$	$\beta$ : La production/ valorisation / traitement
	ACV axée sur les produits		$\beta$ : La demande
L'unité fonctionnelle	Imputation / Substitution	$\gamma$	$\gamma$ : Le sujet de l'ACV
	Expansion du système		$\gamma$ : Le sujet de l'ACV et des fonctions supplémentaires

#### Archétypes d'objectifs d'une ACV

- **Quantifier les impacts:**
  - Quelle(s) est/sont  $\alpha$  de  $\beta$  de  $\gamma$ ?
- **Identification des options d'amélioration :**
  - Comment pourrait-on diminuer les impacts de  $\beta$  de  $\gamma$ , afin de diminuer  $\alpha$  ?
- **Prise de décision:**
  - *Impacts mondiaux/benchmarking* : Est-ce que  $\beta$  de  $\gamma$  a une/des  $\alpha$  moins élevé(s) que son alternative ?
  - *Gestion de portefeuille environnemental* : Est-ce que [partie prenante] est responsable de moins d'impacts à cause de  $\beta$  de  $\gamma$  que dans une situation alternative ?

#### 4. Sous-objectif 3 : Identifier les manques de cohérence actuels et les problèmes non résolus en ce qui concerne la modélisation du recyclage dans les ACV

Du cadre de la Figure 1, il apparaît que, dans une ACV attributionnelle, une situation multifonctionnelle est résolue par une approche d'imputation. Cependant, le cadre ne donne pas de conseils sur la façon d'appliquer l'imputation. Trois méthodes de substitution pourraient être appliquées dans une ACV conséquentielle. Le choix entre ces méthodes de substitution repose actuellement sur (des hypothèses sur) les élasticités-prix de l'offre et de la demande du matériau recyclé. Alors que les acteurs des métaux de base et des plastiques ont déjà indiqué quelle méthode de substitution convient le mieux à leurs secteurs respectifs, on ne sait pas clairement comment cette préférence peut être traduite dans d'autres secteurs de produits. Les limites de l'élasticité-prix et la nécessité d'autres indicateurs pour représenter les contraintes d'approvisionnement ou de demande de matériaux – qui ne sont pas nécessairement échangés sur le marché – sont discutées au Chapitre 3. En outre, on a constaté que le stockage n'est pas considéré dans les méthodes de substitution actuelles.

Les directives officielles ont été étudiées dans une revue critique concernant le cadre systématique d'allocation dans l'ACV de la Figure 1 au Chapitre 4. Les directives ont été analysées quant à leur cohérence dans leurs procédures d'allocation recommandées. Aucune des directives ne semble être entièrement conforme au cadre. L'approche d'imputation est rarement proposée pour modéliser le recyclage dans une ACV attributionnelle. Si une méthode de substitution est recommandée, la

situation du marché du matériau n'est pas toujours prise en compte. Parmi les directives analysées, l'*ILCD Handbook* fournit l'approche la plus cohérente en proposant une procédure d'allocation unique pour la coproduction et le recyclage, et en considérant différents objectifs d'ACV et différentes situations de marché. Les *General programme instructions for the International EPD® system* fournissent des conseils cohérents en appliquant une approche attributionnelle stricte, bien que la coproduction et le recyclage ne soient pas considérés comme des problèmes de multifonctionnalité égaux.

La première étape vers une modélisation ACV cohérente consiste à traiter la coproduction, le recyclage et la récupération d'énergie selon la même procédure d'allocation. La plupart des directives ne tiennent pas compte des différentes méthodes de modélisation pour les différents objectifs d'ACV et l'objectif qui est représenté par la directive est rarement décrit en détail. La séparation entre les ACV attributionnelles et conséquentielles n'est pas toujours réalisée. Bien que plusieurs directives considèrent l'approche de coupure et la méthode de recyclage en fin de vie comme des méthodes directement opposées, ces approches sont utilisées dans différents types d'ACV qui ne devraient pas être combinés. Au lieu de cela, l'approche de recyclage en fin de vie est directement opposée à la méthode d'exploitation minière urbaine – qui n'est recommandée que par l'*ILCD Handbook* – et ces méthodes sont combinées dans la méthode 50/50. La situation du marché du matériau recyclé indique quelle méthode de substitution est appliquée. Si cela n'est pas pris en compte, les impacts environnementaux calculés pourraient ne pas correspondre aux impacts réels.

Comme il n'y a pas encore de document de référence qui donne des indications cohérentes sur l'allocation dans les situations de recyclage, c'est l'objectif des chapitres suivants de la thèse. Au Chapitre 5, il est démontré que l'approche d'imputation n'est pas seulement applicable à la coproduction, mais aussi aux situations de recyclage. Au Chapitre 6, une méthode conséquente est développée qui facilite le choix entre les trois méthodes de substitution, en fonction de la situation du marché du matériel. D'autres indications permettant d'indiquer quelles propriétés du matériau sont pertinentes pour différentes applications, comment la qualité d'un matériau peut être quantifiée et la manière dont les prix du marché pourraient être déterminés et pourraient être donnés dans les documents PCR et PEFCR car ces paramètres peuvent diverger dans différents secteurs.

## 5. Sous-objectif 4 : Améliorer les procédures de modélisation actuelles pour augmenter leur cohérence

### 5.1. Amélioration des procédures d'allocation pour l'ACV attributionnelle

L'objectif du Chapitre 5 était d'identifier une procédure d'allocation qui répond le mieux aux questions posées dans une ACV attributionnelle et de montrer comment cette procédure peut être appliquée. Il est montré dans le Chapitre 2 que différentes interprétations de l'ACV attributionnelle existent dans le domaine ACV. L'interprétation qui est appliquée dans cette thèse est que « l'ACV attributionnelle vise à évaluer la responsabilité des impacts du sujet de l'ACV ». Cela signifie que la procédure d'allocation devrait refléter le degré de responsabilité des impacts des coproduits d'un processus multifonctionnel. Comme il n'existe aucun moyen objectif d'identifier la procédure d'allocation, notre compréhension de la « responsabilité des impacts » est résumée dans un ensemble de définitions et d'axiomes. Sur la base de cet ensemble, la procédure d'allocation « allocation au point de substitution » (APOS) est identifiée comme la meilleure réponse à la question pour quel impacts un produit est responsable.

Le Chapitre 5 fournit des conseils étape par étape pour appliquer l'allocation au point de substitution à partir d'un sous-système de premier plan (*foreground sub-system*) multifonctionnel. Une approche analytique pour l'ACV axée sur les produits a également été proposée et démontrée. Des formules

sont proposées pour un scénario de recyclage simple, le recyclage des produits complexes et la coproduction. Cela permet de comprendre les interactions entre les produits et les processus dans le système de produit lorsqu'APOS est appliqué. En outre, APOS peut facilement être comparé à d'autres procédures d'allocation, si elles sont représentées de manière similaire.

Le choix de la procédure d'allocation a une grande influence sur le résultat de l'ACV. Bien qu'il ait été constaté que l'APOS – avec l'application de l'allocation économique – est la procédure la plus pertinente pour calculer la responsabilité relative des impacts des coproduits, il est reconnu que ce n'est pas la seule procédure qui pourrait être valide. Une compréhension différente de la « responsabilité des impacts » pourrait conduire à une procédure d'allocation différente. En outre, une interprétation différente de ce qui est calculé dans une ACV attributionnelle aboutirait à une définition d'objectif formulée différemment et pourrait demander une allocation basée sur des propriétés physiques plutôt que sur des valeurs économiques. Bien que la méthode APOS soit conforme aux exigences des normes ISO, il est reconnu que les axiomes sur lesquels la méthode est basée sont subjectifs. Toutefois, il n'est pas possible de choisir objectivement une procédure de répartition. La formulation de ces choix subjectifs dans des déclarations claires pourrait conduire à une transparence accrue et à une reproductibilité des études d'ACV. La dérivation logique de la procédure d'allocation à partir de ces axiomes confère à la procédure d'allocation une base scientifique.

## 5.2. Amélioration des procédures d'allocation pour les ACV conséquentielles

Le Chapitre 6 présente une méthodologie pour identifier les conséquences d'un changement, comme une demande accrue pour un produit. De nombreuses parties de cette méthodologie ont été basées sur les directives actuellement disponibles ; en particulier de Ekvall (2000) et Weidema et al. (2009). Dans les ACV conséquentielles, les conséquences de l'offre ou de la demande d'un matériau sont souvent basées sur l'élasticité-prix. L'utilisation de l'élasticité-prix a des limites en raison de la disponibilité limitée des données qui représentent les matériaux pertinents et les horizons temporels et l'information limitée que fournit l'élasticité-prix. En outre, le stockage a été identifié comme un élément manquant dans la modélisation conséquentielle actuelle.

Plusieurs lacunes de l'application actuelle des ACV conséquentielles ont été abordées au Chapitre 6. Il a été considéré précédemment que la demande d'un coproduit dépendant – c'est-à-dire un produit recyclé ou un coproduit qui ne détermine pas le volume de production d'une activité – peut être contraint, tel que décrit au Chapitre 3. Dans ce cas, on suppose généralement que le produit est traité comme un déchet. Dans le Chapitre 6, nous avons démontré que les coproduits dépendants pour lesquels la demande est contrainte ne sont pas toujours éliminés en tant que déchets. Les produits primaires – tels que le sulfate d'ammonium et plusieurs ETR – qui sont produits en excès sont plutôt stockés. Les stocks – avec les flux de déchets – peuvent être considérés comme des stocks anthropiques. Les stocks anthropiques sont identifiés comme le fournisseur marginal de coproduits dépendants pour lesquels la demande est contrainte.

Il est également couramment supposé dans les ACV conséquentielles que les matières sont échangées sur le marché. Cependant, ce n'est pas toujours le cas. Certains coproduits dépendants sont directement échangés entre deux acteurs dans une chaîne de valeur. Dans cette situation, les deux contraintes d'offre et de demande peuvent être pertinentes. De la même manière que pour les coproduits dépendants qui sont échangés sur le marché, il faut identifier les contraintes qui dominent.

La cohérence de la méthodologie existante pour les ACV conséquentielles est encore améliorée en considérant que chaque processus ne comporte qu'un seul coproduit déterminant. Il a été discuté ailleurs (par exemple, par Weidema et al. (2013)) que certains matériaux n'ont pas de route de production alternative et nécessitent une procédure d'allocation différente. Cependant, dans la

pratique, chaque matériau pourrait être remplacé – pas forcément par un autre matériau, mais aussi par un autre produit ou une technologie, ou même par un système complètement différent qui fournit la même fonction.

Le Chapitre 3 a conclu que les élasticités-prix ne suffisent pas à identifier les contraintes relatives à l'offre et à la demande dans chaque situation et dans tous les groupes de produits. Au Chapitre 6, le ratio  $A$  entre le prix du marché du matériau recyclé et celui du matériau primaire substitué est proposé comme un indicateur alternatif pour identifier les contraintes de la demande. Ce facteur peut fonctionner comme un commutateur entre les trois méthodes de substitution qui ont été identifiées au Chapitre 3:

- La méthode d'exploitation minière urbaine est appliquée lorsque  $A = 0$
- La méthode 50/50 est appliquée lorsque  $A = 0,5$
- La méthode de recyclage en fin de vie est appliquée lorsque  $A = 1$

Cet indicateur représente les préférences existantes dans les secteurs des métaux et des matières plastiques. En outre, la méthode est également applicable à d'autres matériaux. Le facteur  $A$  est intégré à la méthode de substitution axée sur le marché (*the market-driven substitution method*). Cette équation est écrite dans le même style que les formules du Chapitre 3.

Le diagramme de causalité de la Figure 2 est présenté comme un outil pour identifier les processus concernés en raison d'une demande changeante pour un produit ou d'une production changeante par un processus. Il est démontré comment la méthode de substitution axée sur le marché se rapporte au diagramme de causalité. Alors que la formule de substitution axée sur le marché a une portée limitée – car elle suppose que l'approvisionnement du matériau primaire substitué est sans contrainte – le diagramme de causalité permet d'identifier plus en détail les conséquences d'un changement.

La méthode de substitution axée sur le marché a également été présentée sous une forme qui permet d'évaluer des produits complexes et une forme qui applique une terminologie axée sur la production. Une équation simplifiée est également introduite et qui peut être utilisée pour évaluer les impacts environnementaux lorsque les données d'inventaire manquent.

La méthodologie pour les ACV conséquentielles appliquée dans cette thèse se révèle conforme aux normes ISO et présente plusieurs avantages par rapport à d'autres méthodologies conséquentielles, telles que la modélisation d'équilibre partiel. Cependant, il est reconnu que les élasticités-prix amélioreraient la méthodologie de cette thèse sur plusieurs aspects : l'utilisateur marginal pourrait être identifié par une élasticité-prix élevée de la demande et le degré de substituabilité ou de complémentarité de deux coproduits pourrait être identifié par l'élasticité-prix croisés. Le ratio entre le prix du marché du matériau recyclé et celui du matériau primaire substitué est plus facilement disponible que les élasticités-prix et pourrait réduire les produits alternatifs pour lesquels des élasticités devraient être collectées. En outre, les ratios du prix du marché peuvent aider à identifier l'existence de conséquences en aval qui ont lieu après la substitution, qui doivent également être modélisées dans l'inventaire de l'ACV.



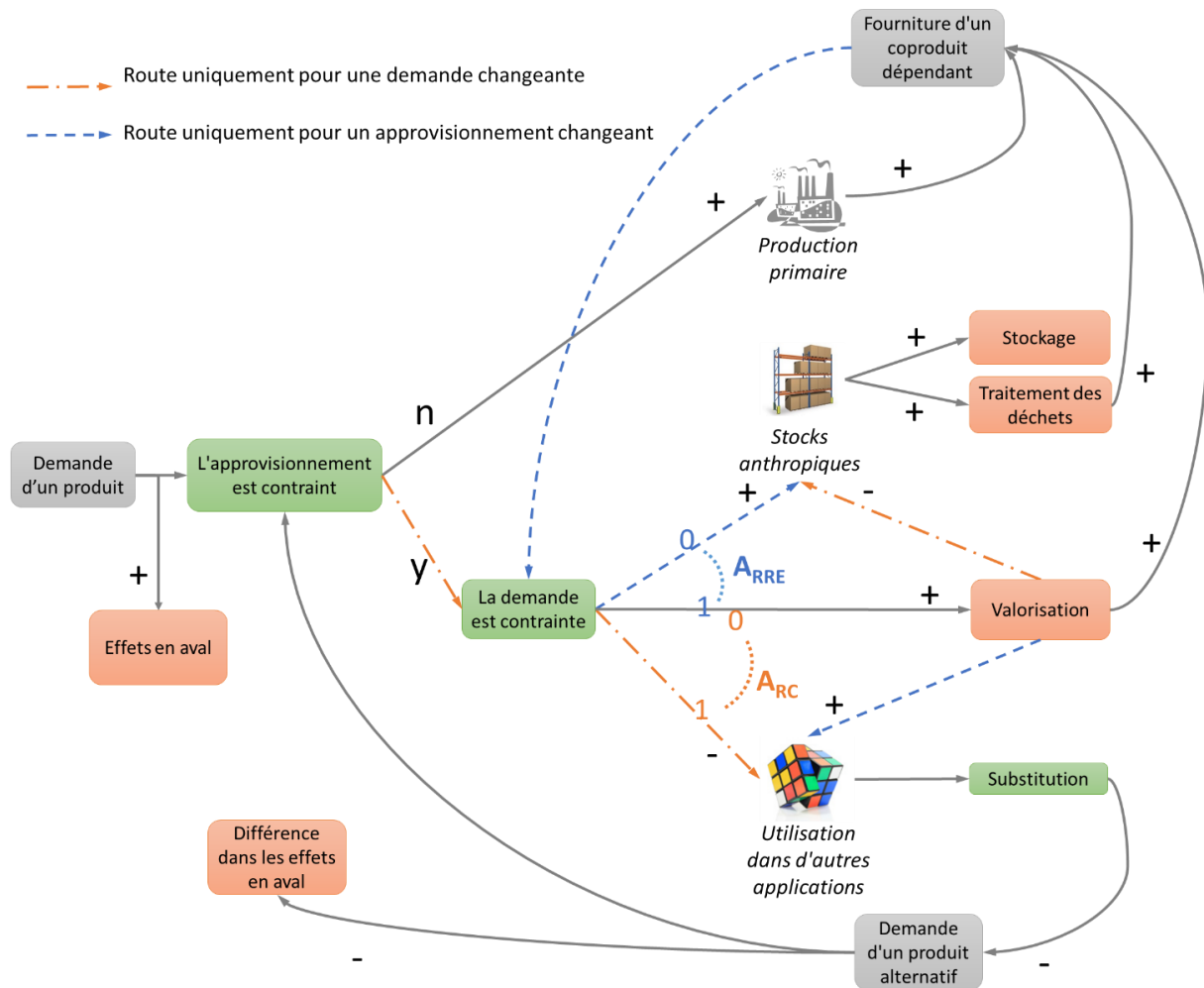


Figure 2 Le diagramme de causalité pour identifier les conséquences d'une demande changeante d'un produit dans un système multifonctionnel. Les signes plus et les signes moins représentent des mécanismes de rétroaction positive et négative, respectivement. Le facteur  $A_{RC}$  est calculé selon le ratio entre le prix du marché du matériau recyclé consommé et celui du matériau primaire substitué dans le cycle de vie actuel.  $A_{RE}$  représente le ratio entre le prix du marché du matériau recyclé fourni et celui du matériau primaire substitué dans le cycle de vie subséquent

6. Sous-objectif 5 : Appliquer les procédures de modélisation aux études de cas de l'industrie chimique afin de démontrer et tester leur applicabilité et leur pertinence

Les procédures de modélisation développées dans les Chapitres 3, 5 et 6 sont testées sur les trois études de cas de Solvay qui ont été introduites au Chapitre 2. L'étude de cas sur le recyclage des ETR est entièrement publiée au Chapitre 7 de la thèse.

## 6.1. Application du cadre systématique

Le Chapitre 7A présente l'objectif de l'étude de cas sur le recyclage des ETR des lampes fluorescentes en fin de vie. La définition de l'objectif contient des éléments qui influencent la procédure d'allocation appliquée dans l'étude de cas. Le cadre systématique du Chapitre 3 a été appliqué pour identifier la procédure d'allocation appropriée, en fonction de ces éléments.

Tout d'abord, le cadre systématique du Chapitre 3 a été mis à jour avec la méthode d'imputation APOS (Chapitre 5) et la méthode de substitution axée sur le marché du Chapitre 6. L'objectif du Chapitre 7A a montré la nécessité d'une ACV attributionnelle et d'une ACV conséquentielle. De plus, des ACV axées sur les produits et axées sur les processus sont menées. Les paramètres pertinents qui influent sur l'approche ACV sont résumés dans le Table 7A-2. A partir de ces paramètres, les archétypes d'objectifs

peuvent être formulés. Ces archétypes d'ACV sont menées dans l'étude de cas attributionnelle du Chapitre 7B et l'étude de cas conséquentielle du Chapitre 7C.

Table 2 Résumé des paramètres qui contribuent aux archétypes d'objectifs de l'ACV

Éléments de la définition des objectifs d'ACV	L'approche ACV	Blocs de construction des archétypes d'objectifs d'ACV
La perspective de l'ACV	ACV attributionnelle	$\alpha$ : La responsabilité des impacts
	ACV conséquentielle	$\alpha$ : Les conséquences sur les impacts mondiaux
La raison de mener l'étude	ACV axée sur les processus	$\beta$ : La production/ valorisation / traitement
	ACV axée sur les produits	$\beta$ : la demande
L'unité fonctionnelle	Imputation / Substitution	$\gamma$ : 1 kg de YOX recyclé prêt pour l'expédition $\gamma$ : 1 lampe fluorescente
	Expansion du système	$\gamma$ : 1 kg de YOX recyclé, 2.05 kg de verre recyclé, 0.18 kg de lanthane recyclé, 0.14 kg de cérium recyclé, 0.07 kg de terbium recyclé, 0.0029 kg d'euporium recyclé résiduel et 9.92 kg de poudre phosphore des lampes fluorescentes usées

## 6.2. ACV attributionnelle du recyclage des terres rares des lampes fluorescentes en fin de vie

Le Chapitre 7B présente une étude de cas attributionnelle sur le recyclage des ETR à partir de lampes fluorescentes. Basé sur des éléments du cadre systématique du Chapitre 3, 11 questions de recherche ont été formulées qui représentent des archétypes des définitions de l'objectif de l'ACV. Ces définitions de l'objectif visent à identifier la responsabilité des impacts du processus de recyclage de YOX, le produit « YOX recyclé » ainsi que les impacts d'une lampe utilisant du YOX recyclé.

L'ACV axée sur les processus a montré que le processus de valorisation de YOX et d'autres ETR des lampes fluorescentes usées est responsable d'impacts environnementaux beaucoup plus faibles que ceux de la voie de production primaire de ces matériaux. L'analyse détaillée a montré que les impacts du processus de recyclage sont principalement causés par le traitement de la poudre de phosphore. Ce serait un bon point de départ si les impacts du processus devaient être réduits.

L'allocation a été appliquée pour calculer les impacts qui peuvent être attribués au YOX recyclé dans une ACV axée sur les produits. Il est montré que le principal contributeur aux impacts du YOX recyclé est l'utilisation du mélange ETR à partir de lampes fluorescentes usées, qui porte des impacts liés à la lampe. Il pourrait être plus difficile de réduire ces impacts, en raison du fait que la lampe fluorescente est en dehors de la sphère d'influence d'une entreprise qui ne produit que des ETR. Les impacts pourraient être réduits en identifiant d'autres sources d'ETR recyclés que les lampes fluorescentes. Cependant, un utilisateur du YOX recyclé est déjà responsable d'impacts inférieurs à ceux d'un utilisateur de YOX primaire. En outre, si un producteur de ETR décide de produire plus de YOX recyclé au détriment de YOX primaire, le profil d'impact de l'entreprise serait amélioré.

Néanmoins, une lampe fluorescente impliquée dans la valorisation de la poudre de phosphore pour recycler les YOX n'est pas responsable des impacts plus faibles qu'une lampe qui n'est pas recyclée. Les impacts d'une lampe peuvent être principalement diminués par l'utilisation d'aluminium recyclé, de mercure recyclé et de verre recyclé. Le fait que la consommation d'ETR en quantité qui reflète une

boucle fermée n'affectant pas les impacts de la lampe, est causé par le faible taux de recyclage en fin de vie des ETR. Il est démontré qu'un contenu élevé de YOX recyclé améliore le profil environnemental de la lampe.

Les archétypes des objectifs attributionnels sont issus de la définition de l'objectif du Chapitre 7A. Le cadre systématique a montré que, dans ces types de définitions de l'objectif, les situations multifonctionnelles pourraient être résolues par l'expansion du système ou de l'imputation. L'étude de cas du Chapitre 7B a démontré que ces procédures d'allocation peuvent effectivement être appliquées aux matériaux recyclés dans une ACV attributionnelle et fournir des résultats pertinents. La méthode d'imputation qui a été développée au Chapitre 5 semble être applicable à la coproduction et au recyclage, et la méthodologie étape par étape du Chapitre 5 s'est révélée utile pour appliquer la méthode APOS. On a démontré comment les équations du Chapitre 5 sont appliquées. En outre, le ratio A du prix du marché qui identifie les contraintes de la demande dans les ACV conséquentielles s'est avéré également utile dans cette ACV attributionnelle. Ce facteur a été utilisé pour déterminer la comparabilité de deux systèmes de produits dans l'ACV axée sur les processus.

À partir de l'analyse d'impact, il est apparu que différents types de résultats ont été générés pour chaque définition d'objectif. Cependant, il faut reconnaître que les résultats ont plusieurs limites. La phase d'objectif de l'ACV a influencé la collecte d'inventaire. Par conséquent, les résultats ne peuvent être utilisés dans d'autres études d'ACV avec différentes définitions de l'objectif. Au cours de la collecte d'inventaire, plusieurs sources d'incertitudes pourraient être identifiées, liées aux processus choisis en arrière-plan, ainsi qu'aux données utilisées pour appliquer l'allocation. Cependant, une analyse d'incertitude a révélé que les conclusions de l'étude sont solides. En outre, la méthodologie d'évaluation d'impact est une source d'incertitude, qui n'est pas encore abordée dans cette thèse.

Les résultats de la méthode APOS sont parfois difficiles à interpréter, car certains impacts semblent indépendants du produit étudié. Cependant, cette thèse vise à identifier une procédure d'allocation qui fournit des résultats pertinents pour les objectifs industriels. Par conséquent, l'interprétation des résultats de cette étude ACV attributionnelle dans un contexte industriel est discutée plus en détail au Chapitre 8.

### 6.3. ACV conséquentielle du recyclage des terres rares des lampes fluorescentes en fin de vie

L'ACV dans Chapitre 7C vise à calculer les impacts causés par la production de YOX recyclé et l'utilisation de YOX recyclé dans une lampe fluorescente. Pour cela, en fonction de la définition de l'objectif du Chapitre 7A, 10 archétypes d'objectif de l'ACV ont été formulées qui tous demandent des informations légèrement différentes de l'ACV.

Les conséquences d'une valorisation accrue et d'une demande accrue pour le YOX recyclé ont été identifiées à l'aide du diagramme de causalité de la Figure 2. Dans les ACV axées sur les processus et axées sur les produits, le coproduit déterminant des processus, le fournisseur ou l'utilisateur de produits marginaux et de substituts pour les coproduits dépendants en forte demande doivent être identifiés. Cela était assez fastidieux, surtout dans cette étude de cas sur les ETR. Les ETR sont des matériaux difficiles à analyser dans une ACV conséquentielle du fait que ces éléments sont toujours produits comme coproduits, la situation du marché des éléments est assez convergente et les substituts ne sont pas facilement disponibles.

L'ACV axée sur le processus de recyclage de YOX a montré que plusieurs autres coproduits sont également produits : le cérium recyclé, le lanthane recyclé, le terbium recyclé, l'euporium recyclé et le verre recyclé. Les effets d'une offre accrue de ces produits – et une diminution de la demande pour

leurs équivalents primaires – ont été évalués avec le diagramme de causalité. Ce diagramme a montré les effets suivants :

- Le recyclage du verre évite la production primaire de verre pour 7%
- Le recyclage du cérium et du lanthane évite l’approvisionnement de ces éléments à partir des stocks d’ETR primaires
- Le recyclage du terbium et de l'euporium conduit à une utilisation accrue de ces éléments par leurs utilisateurs marginaux respectifs

L'utilisateur marginal de l'euporium était supposé être la lampe fluorescente. L’euporium ne peut pas être remplacé par un autre élément, mais une lampe fluorescente peut être remplacée par un autre type de lampe. En raison des incertitudes concernant le substitut de l'euporium, différents scénarios ont été analysés :

- Les lampes fluorescentes ne font que concurrencer les lampes LED
- Les lampes fluorescentes sont en concurrence pour 50% avec des lampes LED et 50% avec des lampes halogènes
- Les lampes fluorescentes ne font que concurrencer les lampes halogènes
- Les lampes fluorescentes deviennent superflues, et l'euporium est fourni à partir de stocks

La consommation d’électricité en aval est considérée comme la seule différence entre ces scénarios. La situation du marché de la lampe fluorescente était un facteur décisif dans l'évaluation des impacts du processus de recyclage de YOX :

- Le recyclage supplémentaire de YOX a un impact sur l'environnement lorsque cela entraîne une transition différée vers un éclairage LED plus économe en énergie
- Le recyclage supplémentaire de YOX est avantageux pour l'environnement lorsque cela entraîne une élimination progressive des lampes halogènes moins efficaces en énergie
- Si l'euporium était disponible en surplus, le recyclage de YOX entraînerait des impacts inférieurs à ceux de la production primaire de YOX dans plusieurs catégories d'impact. Cependant, la production de YOX primaire entraîne des impacts plus faibles sur les changements climatiques, entre autres.

En bref, l'ACV axée sur les processus a montré que le maintien de la disponibilité des ETR au moyen d'un processus de recyclage n'est bénéfique pour l'environnement que lorsque ces éléments permettent la production accrue de lampes fluorescentes et les lampes fluorescentes sont utilisées pour remplacer les lampes halogènes moins efficace en énergie.

Dans l’ACV axée sur les produits, les effets de la demande supplémentaire pour YOX recyclé ont été étudiés pour l'utilisation dans une lampe fluorescente. En outre, il a été évalué si la demande d'une lampe recyclée en fin de vie entraîne des impacts inférieurs à ceux d'une lampe qui n'est pas recyclée. Le ratio A entre le prix de marché de YOX recyclé et de YOX primaire substitué a été utilisé comme indicateur pour déterminer si la demande pour YOX recyclé est contrainte.

L'ACV montre que les impacts causés par une lampe fluorescente peuvent être diminués en utilisant du YOX recyclé lorsque la demande pour le YOX recyclé est faible ou en valorisant la poudre de phosphore en fin de vie lorsque la demande pour YOX recyclé est élevée. Dans la situation actuelle du marché, où le prix du YOX recyclé est relativement élevé et où les lampes fluorescentes peuvent encore remplacer des lampes halogènes, les impacts environnementaux d'une lampe sont diminués si les efforts sont déployés dans une participation active à la collecte de lampes fluorescentes et dans une reprise accrue de YOX à partir de la poudre de phosphore produite en fin de vie de la lampe.

L'utilisation accrue de YOX recyclé dans une lampe n'est pas favorable à l'environnement par l'utilisation de YOX primaire, du fait que l'approvisionnement en YOX recyclé est limité. Cependant, le grand nombre d'incertitudes de l'étude ACV et les limites de l'analyse doivent être pris en compte lorsque les résultats sont utilisés pour soutenir les décisions.

Cette étude de cas conséquentielle a été basée sur les archétypes des objectifs de l'ACV conséquentielle définis au Chapitre 7A. Ces archétypes ont fourni un large éventail de questions de recherche qui ont toutes abouties à des résultats pertinents. Le cadre systématique du Chapitre 3 a montré que les situations multifonctionnelles pouvaient être résolues par substitution – et plus précisément par la méthode de substitution axée sur le marché qui a été développée au Chapitre 6. L'application des équations de la méthode de substitution axée sur le marché a été démontrée dans cette étude de cas. Le ratio entre le prix du marché du matériau recyclé et celui du matériau primaire substitué s'est révélé être un indicateur utile pour déterminer si un recyclage supplémentaire substitue la production de matériaux primaires ou évite le traitement des déchets.

## 7. Sous-objectif 6 : Identifier comment les procédures de modélisation peuvent fournir des informations d'intérêt industriel

Les études de cas qui ont été menées dans cette thèse ont donné plusieurs points de vue concernant l'application des procédures d'allocation et l'interprétation des ACV attributionnelle et conséquentielle. Il existe une discussion en cours dans la communauté ACV sur le choix entre ces approches de modélisation de l'allocation dans l'ACV. Le Chapitre 8 examine le choix entre les approches d'un point de vue industriel. Une distinction est faite entre les objectifs internes et externes d'intérêt industriel. Les objectifs internes se réfèrent aux applications dans la zone d'influence d'une entreprise. Les objectifs externes s'appliquent à l'utilisation d'informations issues de l'ACV qui influencent indirectement les opérations d'une entreprise, par exemple par les décideurs.

Les ACV attributionnelle et conséquentielle sont jugées pertinentes toutes les deux pour les objectifs internes d'intérêt industriel – par exemple pour le développement de produits, la gestion de la chaîne d'approvisionnement ou le marketing. Dans l'ACV attributionnelle, l'allocation a été appliquée avec la méthode "allocation au point de substitution". Cependant, l'imputation pourrait être évitée dans une ACV axée sur les processus. Une ACV axée sur les processus nécessite moins de données, alors que l'applicabilité des résultats est limitée du fait que les impacts d'un produit spécifique du processus ne sont pas identifiés. Par conséquent, de la même manière que le choix entre différentes approches ACV, le choix entre une ACV axée sur les processus et une ACV axée sur les produits dépend de l'application prévue et du public cible. Si une ACV axée sur les produits est requise, l'APOS peut être appliquée. Cela entraîne une augmentation de la collecte de données et les résultats sont parfois difficiles à interpréter. Cependant, la méthode APOS peut fournir à une entreprise des informations relatives aux risques (d'approvisionnement) potentiels causés par des impacts environnementaux en amont ou en aval dans le cycle de vie du produit. Cela pourrait représenter le pilier environnemental de la durabilité des opérations de l'entreprise, c'est-à-dire si l'utilisation future d'un matériau pourrait être compromise en raison de (réglementations pour réduire) l'impact environnemental. Cette information n'est pas fournie par l'approche de coupure, bien que dans certaines situations, l'approche de coupure puisse être utilisée pour simplifier l'analyse. Au lieu d'APOS, la méthode de recyclage en fin de vie est souvent utilisée pour modéliser le recyclage dans les ACV attributionnelles. Cette méthode (conséquentielle) indique si le recyclage est avantageux pour l'environnement. Cependant, il ne fournit pas d'informations sur la durabilité de l'utilisation du matériel.

En ce qui concerne les ACV conséquentielles, le ratio A entre le prix du marché du matériau recyclé et celui du matériau primaire substitué a été introduit comme indicateur des contraintes de la demande.

En outre, ce ratio peut également indiquer si deux produits sont de bons substituts ou si des effets en aval ont lieu. Ce type d'information est également utile dans une ACV attributionnelle qui compare deux systèmes de produits qui fournissent la même fonction.

L'ACV conséquentielle calcule si la production ou la demande d'un produit est avantageuse pour l'environnement. Les résultats d'une ACV conséquentielle axée sur les processus peuvent être utilisés par une entreprise pour renforcer sa réputation d'être « conscient de l'environnement » et pourrait soutenir les demandes de soutien financier. Les résultats d'une ACV conséquentielle axée sur les produits sur un produit recyclé pourraient être utilisés pour des activités de marketing par une entreprise qui utilise ce produit dans ses applications. Le ratio  $A$  peut être utilisé pour déterminer quelle activité de recyclage doit être encouragée. Le contenu recyclé de l'application devrait être favorisé si la demande pour le matériau recyclé est généralement faible et si le ratio  $A$  est inférieur à 1, alors que la recyclabilité de l'application peut être soulignée si l'approvisionnement supplémentaire de matière recyclée est avantageuse pour l'environnement et si  $A > 0$ .

En outre, l'ACV conséquentielle peut donner à une société des informations liées à d'autres risques dans le cycle de vie d'un produit, en plus des impacts environnementaux. Ceux-ci sont liés aux perturbations potentielles de l'offre et à la position relative d'un produit à ses substituts en considérant la transition vers des technologies plus respectueuses de l'environnement. En ce qui concerne ces aspects, l'ACV conséquentielle a des similitudes avec une évaluation de criticité des ressources. Celle-ci intègre le risque d'approvisionnement et les vulnérabilités aux contraintes potentielles liées à l'accessibilité des ressources, en plus des impacts environnementaux. Par conséquent, les résultats d'une ACV conséquentielle pourraient également refléter des aspects de la durabilité socio-économique d'une entreprise.

Les ACV attributionnelle et conséquentielle sont également des approches pertinentes pour les objectifs extérieurs des intérêts industriels, comme la communication avec les décideurs. Les ACV conséquentielles peuvent informer les décideurs sur les produits et les processus qui sont bénéfiques pour l'environnement. Les résultats d'une ACV attributionnelle montrent quelles applications seront affectées par les législations des décideurs. Sur la base de cette information, les décideurs politiques peuvent soutenir des produits ou des processus favorables à l'environnement par des subventions ou un système fiscal adéquat. La législation pourrait être adaptée d'une manière qui n'affecte pas négativement les produits et les processus favorables à l'environnement. En outre, l'approvisionnement de certains matériaux peut être contraint – tels que les produits recyclés ou certains coproduits primaires – alors que ces matériaux pourraient diminuer les impacts d'une application ou même la rendre bénéfique pour l'environnement. Les décideurs politiques pourraient intervenir pour détourner ces matériaux vers des applications favorables à l'environnement, ce qui pourrait diminuer les risques potentiels liés aux impacts environnementaux ou aux perturbations de l'offre dans la chaîne de valeur de ces applications. Ainsi, cela augmenterait leur durabilité globale, englobant les aspects environnementaux et socio-économiques mentionnés ci-dessus.

Le ratio  $A$  entre le prix du marché du matériau recyclé et celui du matériau primaire substitué dans la méthode de substitution axée sur le marché permet de soutenir les décisions politiques de subventions qui stimulent l'utilisation de produits ou de technologies favorables à l'environnement. Les subventions peuvent être attribuées aux fournisseurs de déchets lorsque le processus de recyclage est plus coûteux que le processus de traitement des déchets ou aux utilisateurs du matériau recyclé lorsque le prix du matériel recyclé est supérieur à celui des produits primaires. Lorsque le prix du marché des matériaux recyclés ne reflète pas l'existence de contraintes de la demande, les subventions peuvent être attribuées au fournisseur ou à l'utilisateur du matériau recyclé. En outre, les subventions peuvent aider les entreprises ou les consommateurs à surmonter les coûts d'investissement initiaux

qui empêchent l'utilisation du matériel recyclé. Les mesures politiques visant à influencer les résultats d'une imputation économique dans les ACV attributionnelles ne sont pas considérées comme utiles, car cela pourrait masquer les risques potentiels liés aux fournisseurs en amont ou aux étapes du cycle de vie en aval. Outre les subventions, les décideurs politiques pourraient appliquer des taxes pour stimuler les comportements environnementaux préférables. Les taxes pourraient être basées sur des flux élémentaires qui sont mesurés dans le système de premier plan. Ces flux ont une plus faible incertitude et ne nécessitent pas de différenciation entre l'ACV attributionnelle ou conséquentielle. Les taxes peuvent être intégrées dans les prix des produits, qui peuvent être transférés entre les acteurs du cycle de vie du produit.

On peut conclure que les approches attributionnelle et conséquentielle de l'ACV fournissent des informations utiles et complémentaires aux entreprises et aux décideurs. La méthode APOS appliquée dans cette thèse reflète la durabilité environnementale d'une chaîne de valeur, qui n'est pas représentée par d'autres méthodes souvent utilisées dans l'ACV attributionnelle. La méthode conséquentielle développée dans cette thèse permet d'améliorer une étude attributionnelle en évaluant la comparabilité de deux systèmes de produits. En outre, la méthode fournit des informations sur les impacts ou les avantages environnementaux causés par l'utilisation du produit, qui pourraient être appliqués aux activités de marketing. De plus, l'ACV conséquentielle fournit des informations sur les aspects de la durabilité socio-économique d'une entreprise. Les décideurs peuvent utiliser les résultats d'une ACV conséquentielle pour évaluer la performance environnementale d'une activité et stimuler la demande de produits respectueux de l'environnement, ce qui pourrait constituer une base pour une économie plus verte et plus circulaire.

## 8. Conclusions

Le recyclage est une solution potentielle pour diminuer les impacts environnementaux ainsi que d'autres problèmes liés à l'utilisation des matériaux. Le fait que le recyclage soit effectivement bénéfique pour l'environnement peut être évalué avec une ACV. Cependant, la modélisation du recyclage dans l'ACV est un sujet de discussion en cours. Cette thèse avait pour objectif de développer une approche cohérente et scientifique pour la modélisation du recyclage dans l'ACV, qui produit des résultats pertinents pour les entreprises. Pour atteindre cet objectif, plusieurs sous-objectifs ont été formulés au Chapitre 1. Chacun des chapitres de cette thèse a traité l'un de ces sous-objectifs.

Le Chapitre 2 donne l'état de l'art de la modélisation du recyclage dans l'ACV. Le recyclage – ainsi que la coproduction en général – rend un système de produit multifonctionnel. Dans l'ACV, les systèmes de produit multifonctionnels nécessitent une procédure d'allocation pour identifier les impacts environnementaux liés aux cofonctions du système de produit. L'allocation est, cependant, un sujet très débattu parmi les experts ACV. Les directives et les praticiens ACV ont des préférences divergentes pour les procédures d'allocation, alors que les développements scientifiques suggèrent que la procédure d'allocation dépend de l'objectif de l'ACV et du choix entre une approche attributionnelle et conséquentielle.

Un cadre systématique des procédures de modélisation pour le recyclage qui est cohérent et scientifique a été développé au Chapitre 3. À cette fin, un état de l'art plus détaillé a été présenté sur les procédures d'allocation pour le recyclage. Les procédures d'allocation ont été exprimées par des formules mathématiques qui démontrent les différents mécanismes de chaque procédure. Le cadre systématique montre qu'il existe une différence pertinente entre les ACV axées sur les processus et axées sur les produits pour l'application de l'allocation. Une approche d'imputation est appliquée dans une ACV attributionnelle axée sur les produits et la substitution – soit par la méthode de recyclage en fin de vie, soit la méthode d'exploitation minière urbaine, ou par la méthode 50/50 – dans une ACV conséquentielle axée sur les produits. L'application de l'imputation et de la substitution peut être

évitée dans une ACV axée sur les processus par l'expansion du système. Par conséquent, la procédure d'allocation dépend de différents éléments de la définition de l'objectif de l'ACV : la perspective, la raison pour mener l'étude, l'application prévue et la définition de l'unité fonctionnelle. Sur la base de ces éléments, les archétypes des définitions d'objectif de l'ACV sont formulés qui représentent des questions de recherche d'ACV typiques soutenues par le cadre.

Le cadre systématique qui est développé au Chapitre 3 est limité dans le sens où il ne donne pas de conseils sur la façon dont l'imputation peut être appliquée dans une ACV attributionnelle, et comment le choix peut être fait entre les trois méthodes de substitution pour différents types de matériaux dans un ACV conséquentielle. Ce choix dépend de la situation du marché du matériel, qui pourrait être quantifiée par les élasticités-prix. L'utilisation des élasticités-prix est limitée, du fait qu'elles soient difficiles à calculer. Elles pourraient ne pas être disponibles pour le matériel étudié, elles peuvent être agrégées ou se référer à un horizon temporel différent de celui de l'étude ACV. En outre, la littérature existante faisait référence à de multiples boucles de recyclage et au stockage comme des éléments manquants qui devraient être considérés dans une approche d'allocation.

De nombreuses directives (gouvernementales) sont disponibles fournissant des recommandations spécifiques sur l'allocation. Ces directives sont examinées dans une revue critique dans le Chapitre 4 concernant la cohérence de leurs recommandations avec le cadre systématique du Chapitre 3. Aucune des directives n'est entièrement conforme au cadre. L'imputation est rarement proposée pour modéliser le recyclage dans une ACV attributionnelle. Si la substitution est recommandée, la situation du marché du matériau n'est pas toujours prise en compte. Seul l'*ILCD Handbook* propose la méthode d'exploitation minière urbaine pour les matériaux recyclés qui sont en faible demande. Les différents types de définitions de l'objectif de l'ACV ne sont souvent pas pris en compte et l'objectif représenté par la directive est rarement décrit en détail. Souvent, différentes procédures d'allocation sont recommandées pour différents types de situations multifonctionnelles. En outre, certaines directives appliquent explicitement une approche attributionnelle tout en combinant cela avec des éléments d'une ACV conséquentielle. La revue critique a montré que des directives claires pour mener une ACV attributionnelle et conséquentielle de manière cohérente manquent encore. Ces directives sont fournies aux Chapitres 5 et 6 de la thèse.

L'approche d'imputation dans l'ACV attributionnelle est portée par une base scientifique donnée au Chapitre 5 en appliquant une méthode axiomatique. De ce fait, l'« allocation au point de substitution » avec l'allocation économique a été identifiée comme l'approche d'imputation qui représente le mieux la responsabilité des impacts d'un produit. Avec une nouvelle équation, il est démontré que l'approche d'imputation peut calculer l'inventaire d'un produit qui a été recyclé plusieurs fois avant, tout en différenciant le contenu recyclé et le taux de recyclage en fin de vie.

Au Chapitre 6, la nouvelle méthode de substitution axée sur le marché a été introduite pour les ACV conséquentielles dans lesquelles le ratio entre le prix du marché du matériau recyclé et celui du matériau primaire substitué permet d'indiquer si le recyclage supplémentaire substitue la production de produits primaires ou évite le traitement des déchets. Ce ratio permet d'opérer en tant que commutateur entre la méthode de recyclage en fin de vie, la méthode 50/50 et la méthode d'exploitation minière urbaine. En outre, ce ratio aide à identifier les substituts appropriés et les effets indirects en aval.

De plus, dans le Chapitre 6, nous avons développé un diagramme de causalité qui peut être utilisé comme outil pour identifier les effets indirects de l'offre ou de la demande d'un matériau dans une ACV conséquentielle. Ce diagramme comprend tous les effets qui sont calculés par la méthode de substitution axée sur le marché. Le diagramme distingue entre des coproduits déterminants – par



exemple produits primaires – et coproduits dépendants, e.g. produits recyclés. En outre, on considère que certains produits primaires ne sont produits que comme coproduits dépendants, qui sont donc également modélisés par la substitution axée sur le marché.

Les coproduits dépendants dont la demande est faible ne sont pas nécessairement traités comme des déchets. Les coproduits dépendants primaires sont plus susceptibles d'être stockés. Les stocks sont considérés – en même temps que les flux de déchets et les produits en fin de vie – comme sources précieuses de matériel. Par conséquent, les stocks anthropiques sont identifiés comme le fournisseur marginal de coproduits dépendants pour lesquels la demande est contrainte. La production des stocks anthropiques est appelée recyclage ou « valorisation ».

La formulation des archétypes des définitions de l'objectif de l'ACV et l'application du cadre systématique ont été démontrées par une étude de cas sur le recyclage des terres rares à partir de lampes fluorescentes au Chapitre 7. Cette étude de cas a permis d'illustrer l'application des procédures d'allocation « allocation au point de substitution » et la méthode de substitution axée sur le marché. L'étude de cas attributionnelle a montré que les éléments de terres rares recyclés sont responsables des impacts environnementaux plus faibles que les éléments de terres rares primaires. L'étude de cas conséquentielle a démontré que le recyclage des terres rares est bénéfique pour l'environnement, tant que ces éléments restent utilisés dans des lampes fluorescentes afin de remplacer les lampes halogènes moins éco-énergétiques.

Le Chapitre 8 a montré que les ACV attributionnelle et conséquentielle fournissent des informations pertinentes aux entreprises. L'ACV attributionnelle détermine si les opérations d'une entreprise sont durables sur le plan environnemental. Dans les ACV conséquentielles, le ratio A entre le prix du marché du matériau recyclé et celui du matériau primaire substitué permet d'indiquer si le contenu recyclé ou la recyclabilité d'un produit est avantageux pour l'environnement. Cette information pourrait être utilisée dans les activités de marketing. L'ACV conséquentielle montre en outre des similitudes avec une évaluation de la criticité des ressources. Par conséquent, une ACV conséquentielle pourrait indiquer si les opérations d'une entreprise sont durables d'un point de vue socio-économique. Également pour les décideurs politiques, les ACV attributionnelle et conséquentielle sont toutes les deux pertinentes : l'ACV conséquentielle montre quels produits contribuent à une société plus respectueuse de l'environnement. L'ACV attributionnelle montre quels produits sont affectés par les politiques gouvernementales. Les règlements pourraient être conçus de manière à ce que les produits favorables à l'environnement deviennent plus durables. En outre, la méthode de substitution axée sur le marché peut aider à déterminer si les subventions pourraient créer une situation de marché qui stimule les comportements favorables à l'environnement.

L'objectif de cette thèse était de développer une approche cohérente et scientifique pour la modélisation du recyclage dans l'ACV pour produire des résultats pertinents pour les entreprises. Cet objectif a été atteint grâce à l'élaboration d'un cadre systématique de procédures d'allocation. Le choix pour une procédure d'allocation dépend de l'objectif de l'ACV. Les procédures du cadre ont été améliorées pour permettre une application cohérente dans toutes les situations multifonctionnelles de recyclage, ainsi que pour la coproduction. Les procédures d'allocation pour les situations de recyclage développées dans cette thèse se révèlent cohérentes, fondées sur des principes scientifiques et fournissent des informations pertinentes pour les objectifs d'intérêt industriel. En outre, ils sont conformes aux normes ISO 14040 et ISO 14044. Le cadre systématique et les procédures d'allocation peuvent être appliqués par les praticiens ACV et peuvent servir d'inspiration pour les directives futures. La principale limitation du cadre systématique est la dépendance de la procédure d'allocation sur les archétypes des objectifs d'ACV définis dans la thèse.