Teaching Resources on the Sustainable Management of Critical Raw Materials

Trainer's Manual for
Life Cycle Assessment

March 2020

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Table of Contents

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1 Context and Introduction to Training

This booklet is supplementing the teaching materials and the set of further supporting booklets that have been developed to support teachers in conducting training courses related to the sustainable management of critical raw materials.

SusCritMat aims to educate people from Master's student level up, both in industry and academia about important aspects of sustainable critical raw materials. In a novel concept, it introduces courses on these complex and interdisciplinary topics in a modular structure, adaptable to a variety of different formats and accessible to both students and managers in industry. These courses will develop new skills, which will help participants to better understand the impact and role of critical raw materials in the whole value chain; enabling them to identify and mitigate risks. Understanding the bigger picture and the interconnected nature of global business and society is increasingly necessary to and valued by industry.

SusCritMat is an EU-funded project that brings together the technical and pedagogical expertise of leading educational institutions and business partners. It uses and creates teaching materials which can be combined into different course formats.

The collection of training manuals presents the key messages related with the sustainable management of critical raw materials in three major sections:

- Introduction to criticality
- Analysis of criticality
- Solutions for sustainable management

In particular, the solutions part will be in the focus. The intention is to underline the possibilities that are available to approach and implement a circular economy for critical raw materials and the products bearing these. Doing so the concrete actions, i.e. the things that can be done, are highlighted, instead of only mentioning all sorts of associated problems or barriers in the context of CRMs.

The overall goal of the SusCritMat project is to qualify lecturers to teach the topics themselves. Therefore, the teaching resources do not only provide an introduction and improved insight into selected thematic issues, but also deliver a set of teaching materials "ready-to-use".

- Learning targets that will be reached after having taught the courses
- Presentations on the specific topics including also notes on how to present the slides and key messages.
- Group work exercises including the task or question to work on, if applicable further reading on the methodology and the solutions in case of tasks requiring calculations.
- Assessment questions and the correct answers for each specific topic.
- Additional reading for each topic.

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1.1 Training Materials List

The *SusCritMat project* developed the following teaching materials:

Basics
Critical Resources for Emerging Technologies
Criticality
Supply Chain Resilience
Supply Risk Factors
Circularity
Circular Economy
Characterizing the Urban Mine
Circular Business Models
Waste Management and Recycling Potential
Closing Loops on Product Level
Governance
Geopolitical Aspects
Metals & CRM Scenarios
Restricted Substances Legislation
Impact on Society and the Environment
Sustainability Assessment
Responsible Mining
Responsible Sourcing / Certification
Environmental Aspects
Sustainable Materials Usage
CRM and Sustainable Development
Tools
MFA - Material Flow Management
Simulation-based Design for Recycling (DfR)
Good Use of Data
LCA – Life Cycle Assessment
Process Models based on LCA

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1.2 Suggested timetable

The agenda contains a recommended timing for the lecture and exercises. However, depending on the pre-existing knowledge or group size the time can be extended.

- Lecture: 60 minutes
- Exercise: 120 minutes (including 15 minutes break). The exercise can be performed as a group or be an individual assignment.
- Recap: 20 minutes

1.3 Key Messages

This training module introduces the basic concepts and theories of life cycle assessment (LCA). The module includes:

- A presentation on the basics of life cycle assessment
- An Excel-based practicum focusing on the assessment of the environmental impacts of the production of neodymium
- An expansion of the Excel-based practicum to look into the modelling of multi-output procsses and the related principles of allocation of impacts
- The results of the Excel-based exercises
- A short recap presentation on the results of the Excel-based exercise

This module presents the basics of life cycle assessment (LCA). Starting from the benefits of taking the perspective of the full life cycle of product systems, the module presents the philosophy of LCA. Fundamental questions that can be answered using LCA are analysed, with a focus on the avoidance of burden shifting and regrettable substitution. The ISO standard series on LCA is used to describe the various phases of conducting an LCA study, starting from goal and scope definition, inventory analysis, and impact assessment, up to the interpretation phase. Methodological subtleties in the various phases are explained also using intuitive examples. A practicum accompanies the theory lecture. The focus of the practicum is on the development of a full case study. At first, students are guided through the analysis of a simple system with two connected processes. This system allows the exploration of all phases of LCA in detail, with consideration of methodological components such as the selection of system boundaries, and allocation of impacts to

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multi-functional processes. A full case study on the assessment of NdFeB magnets completes the practicum. This part of the practical session allows further refining the LCA skills of the students.

1.4 Learning Objectives

- Understanding of the basics of life cycle assessment (LCA)
- Understanding of the steps involved in a LCA case study, from data collection to interpretation of results
- Comprehending the basic methodological issues of LCA
- Applying LCA to simple case studies

1.5 Additional Reading

- Chomkhamsri, K., Wolf, M.A. and Pant, R., 2011. International reference life cycle data system (ILCD) handbook: review schemes for life cycle assessment. In Towards life cycle sustainability management (pp. 107-117). Springer, Dordrecht.

  Handbook on LCA, basic principles, phases of LCA

- Henriksson, P.J., Heijungs, R., Dao, H.M., Phan, L.T., de Snoo, G.R. and Guinée, J.B., 2015. Product carbon footprints and their uncertainties in comparative decision contexts. *PLoS One*, *10*(3), p.e0121221.
- Guinée, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. *The international journal of life cycle assessment*, *7*(5), p.311.
- Garner, K.L., Suh, S. and Keller, A.A., 2017. Assessing the Risk of Engineered Nanomaterials in the Environment: Development and Application of the nanoFate Model. *Environmental science & technology*, *51*(10), pp.5541-5551.
- Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. and Klüppel, H.J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment*, *11*(2), pp.80-85.
- Cucurachi, S., Borgonovo, E. and Heijungs, R., 2016. A protocol for the global sensitivity analysis of impact assessment models in life cycle assessment. *Risk Analysis*, *36*(2), pp.357-377

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- Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S., 2009. Recent developments in life cycle assessment. *Journal of environmental management*, *91*(1), pp.1-21.
- Hellweg, S. and i Canals, L.M., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), pp.1109-1113.

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2 Slides and Notes

	
	
	What phase is contributing the most to the impact of a paper cup and why?

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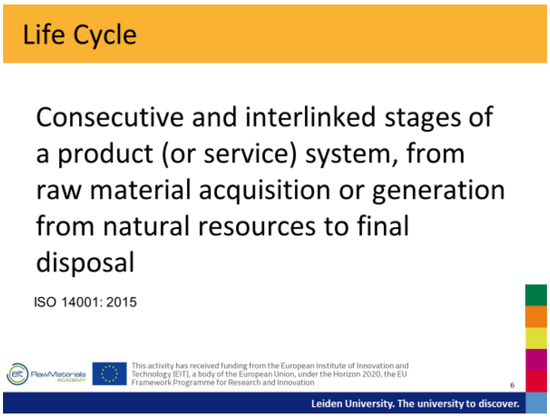
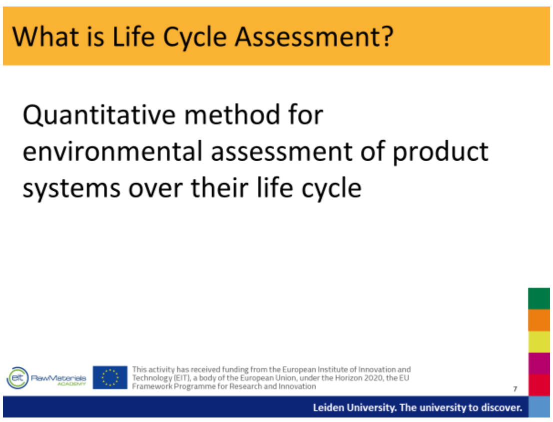
	What is the environmentally best alternative and why?
	
	Here you see a definition of what a life cycle is in the interpretation of the ISO standard on LCA.
	LCA is a quantitative method to assess the environmental impacts of product and service systems. Sometimes the methods and the life-cycle thinking principles are extended to cover costs and social aspects of life cycles. products; strictly spoken it is about product functions (not factories, countries, substances actually not really about products but product functions) a functiona approach, goods/ services providing a function.

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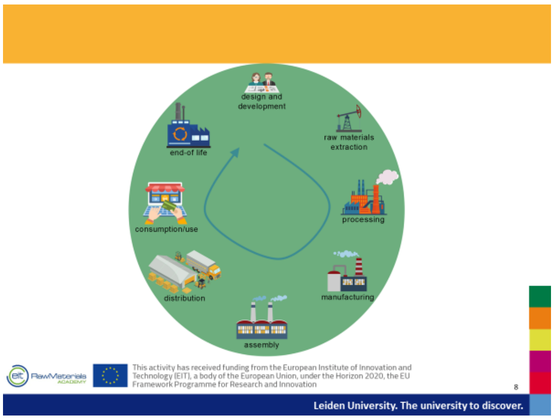
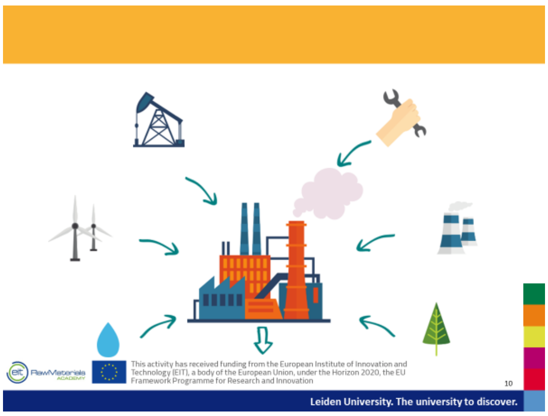
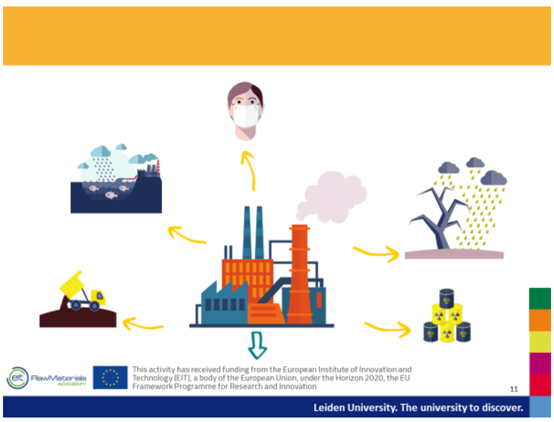
	We see a schematic representation of a life cycle, from R&D to end-of-life. All stages of the life cycle are in principle included in the assessment.
	Let’s take a look at one of the stages of the life cycle, e.g. the processing of resources.
	In order to process resources, and obtain an output and economic and natural inputs are required. These include, for instance, water, wood, and energy and materials.
	All of these inputs and output exchanges determine emissions across the global system we assess. Such impacts can be on ecosystems, marine or land-based, or on the emissions of particles.

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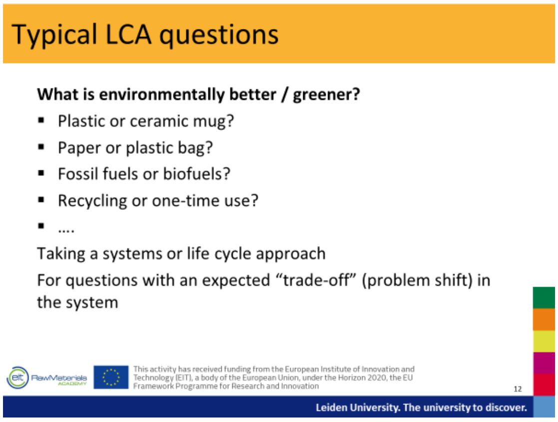
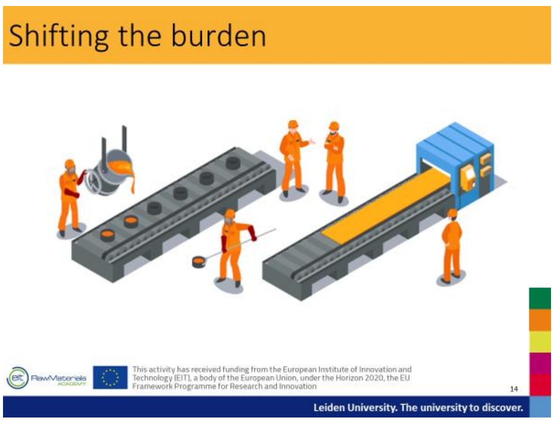


Here you see a typical list of example questions for LCA. These relate to environmentally preferable choices, or to the stages of a life cycle that contribute the most to impacts.

One of the main differences between Environmental risk assessment (ERA) is the scale of the analysis, which is local for ERA and global for LCA. LCA, as a result, mostly deal with average impacts.

LCA aims to account for trade-offs and aims avoiding problem shifting. Think of an electric vehicle => less use emission but making fuel cells needs the extraction of resources such as platinum. Similarly, we want to avoid shifting the burden from one location of the world (Europe), to another (China). Or from an impact category (climate change) to another (toxicity).

Here is an example: off-shore wind turbines do not emit any toxicant or chemical substance when they operate. However, if we take into account the full upstream system of relationships, economic flows, natural inputs that this system triggers to produce electricity, we do have to account for emissions and use of a variety of resources.



These include shipping and transportation, sheet-rolling of steel, extraction of oil, cabling.

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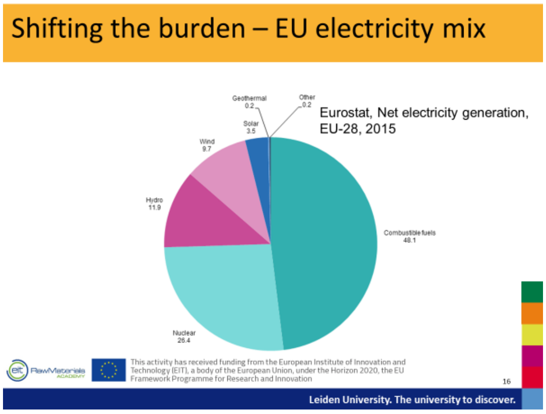
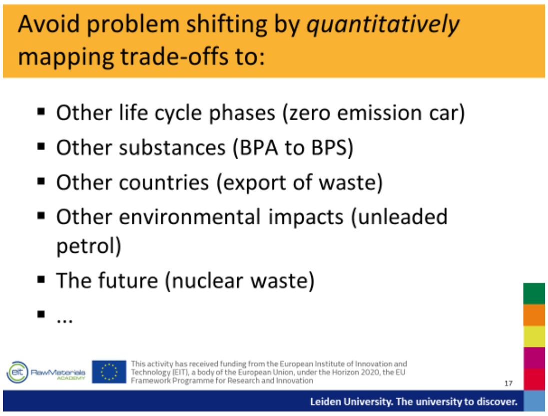
What about an electric car? There are no tailpipe emissions, but certainly emissions upstream and downstream as well.



Downstream we should consider the electricity mix of the country in which the car will operate. If this include combustion fuels for the production of electricity, those will also cause emissions that will have to be associated to the use of electric vehicles as well.



Once again, we want to avoid burden-shifting. A historical example of this is Methyl Tertiary Butyl Ether (MTBE), which is an addition to gasoline for improving combustion and is a substitute for the addition of lead. MTBE is made from butane and natural gas. It has been introduced in America to combat air pollution. Read more: http://www.lenntech.nl/mtbe-btex-verwijdering.htm#ixzz1fb5f5r4P
After MTBE was used as a lead substitute in petrol, the air quality or the air emission pollution was improved, but pollution in the groundwater replaced it. A typical case of shifting an environmental problem from one environmental compartment to another. The controversy over water pollution with MTBE started in the state of California, where a very small number of drinking water sources contain too high a content of this substance. The pollution mainly comes from leaking storage silos, pipelines and underground petrol tanks, but also from spills (spills) or ordinary pollution such as surface water on boats), mowing machines, etc. Why is MTBE undesirable?
MTBE is difficult to break down. It is a substance that dissolves very well in water and poorly

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	adsorbs in soil (that is why conventional water purification technologies have difficulty catching it). Partly for this reason, it is detected earlier (or observed in higher concentrations) as pollution in groundwater than the sister components of gasoline BTEX. The health hazards of MTBE are not yet fully known, but it is suspected that it can be carcinogenic. The guideline for the maximum concentration in water is 20 ppb (20 micrograms per liter). The limit value for being able to taste MTBE in water is 5 ppb. Read more: http://www.lenntech.nl/mtbe-btex-verwijdering.htm#ixzz1fb5SDJYK The addition of a small amount of lead to gasoline (up to September 2004 this was 0.15 grams of lead per liter) provides a lubricating and protective layer of lead oxide on the valve seats. On cars with "soft" valve seats, such as all Land-Rover 2.25 liters and the 2.6-liter 6-cylinder head-side valve (F-head) engines, lead therefore prevents extra wear and possible combustion of these valve seats. With these engines, the valves close directly to the "soft" cast iron of the cylinder head (or cylinder block at the F-head). The valve seats are milled in here, as it were. It is therefore not the (unloading) valves, but the material of the cylinder head, which the lead "urgently" needs. All cars and motorcycles produced after 1986 are (mandatory) suitable for the use of "lead-free" fuel. Models intended for the American market and Japanese markets had this issue even from 1978 onwards. These engines have hardened or used hard metal valve seats, which is a determinant of lead.
	Let’s take a look at the LCA methodology.

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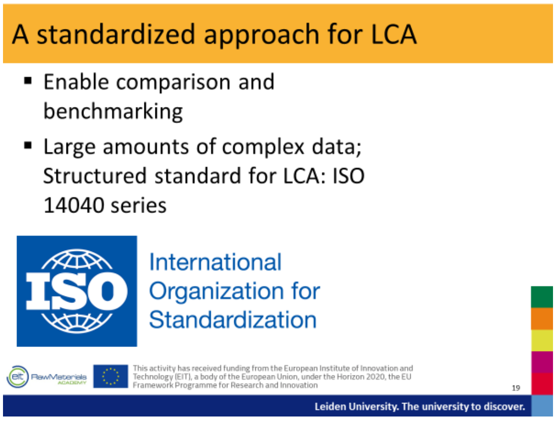
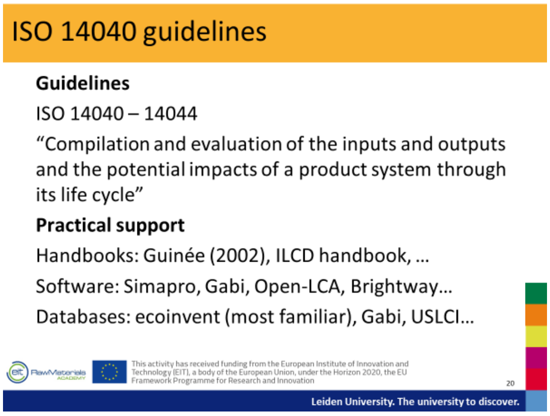


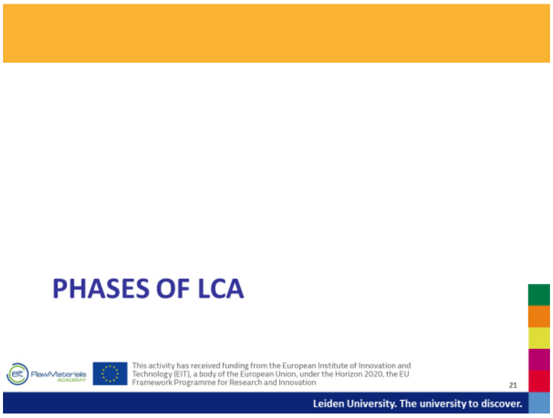
People all used to do it their own way making studies not transparent, not reproducible and hard to understand. What is the value of hard to understand information? Over time consensus has been reached over the standard way of conducting an LCA study, now documented in the ISO14040 series.



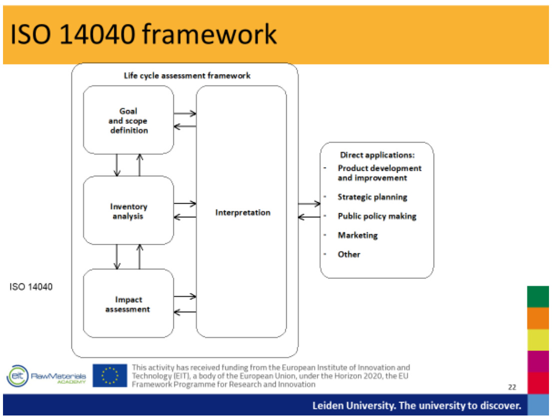
There is a recipe for doing LCA.

And there are some practical tools like software and database to use software for calculations (matrix algebra) databases for common data in the inventory phase (as shown later).

The ILCD handbook provides also guidelines on how to interpret the ISO standard.



Let’s take a look at the standard phases of LCA.



Here, we see the ISO framework for LCA. It comprises the LCA procedure itself, as well as its relation with the direct applications. The four main phases of LCA are concerned with different types of data, assumptions, procedures or calculations. The phases are mutually connected with arrows. These represent flows of information from one phase to another phase. The bidirectional flows stress that LCA is not a sequential process, starting with goal and scope definition and ending with interpretation. Rather, LCA is an iterative process, in which the goal and scope may be refined after inventory analysis,

<table>
<tr>
<td></td>
<td>impact assessment or interpretation, and likewise the inventory analysis may be refined after impact assessment or interpretation. The direct applications are not formally part of the LCA, as LCA is a tool for decision-support. However, they are worth mentioning in relation to the LCA framework itself.

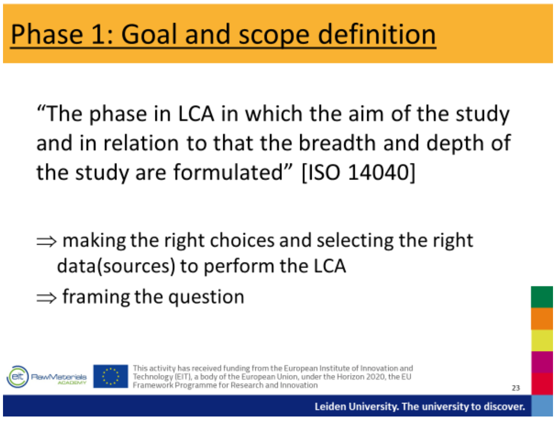
Structured framework

Four phases:

Iterative process can be in parallel

Rules and requirements

Transparency in reporting

Provides a common language so that we know what we are talking about</td>
</tr>
<tr>
<td>
</td>
<td>First phase and more or less the primary research design but ITERATIVE PROCESS

Goal

Scope

Procedural aspects (how to deal with data gaps, allocation,…?)</td>
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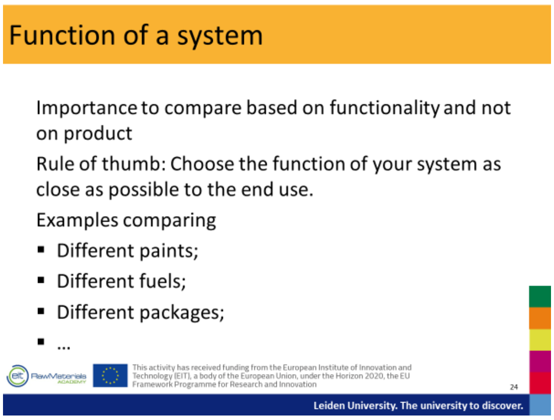
<tr>
<td>
</td>
<td>At the basis of LCA, there is the concept of function. What is the function of the system under assessment?</td>
</tr>
</table>

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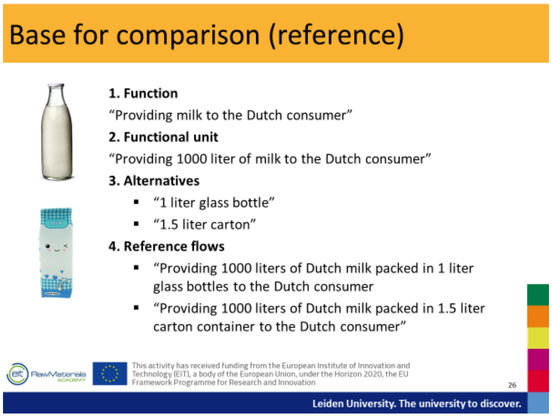
The functional unit is a crucial element in LCA, with many consequences for the meaning of the results of LCA. It is essentially the basis of comparison of different product alternatives that fulfill an equivalent function. The functional unit is an expression of what is considered to be this equivalent. Light bulbs produce light, so in a comparison of two different light bulbs, the functional unit must be phrased in terms of light. For instance, 1000 hours of light of a certain intensity might be a good functional unit. The choice of functional unit directly steers the calculations.

question:

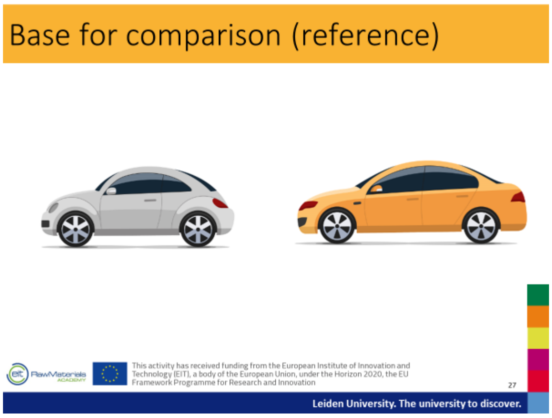
FU for paint?

FU for a TV?

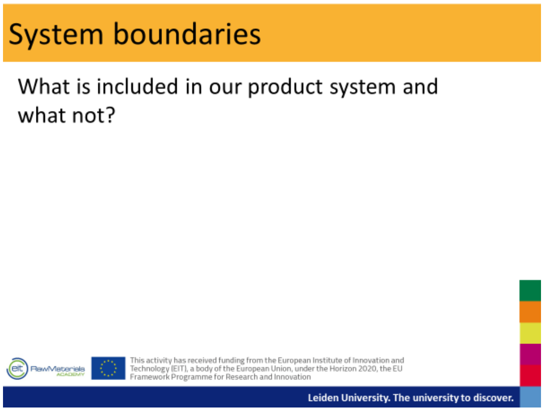
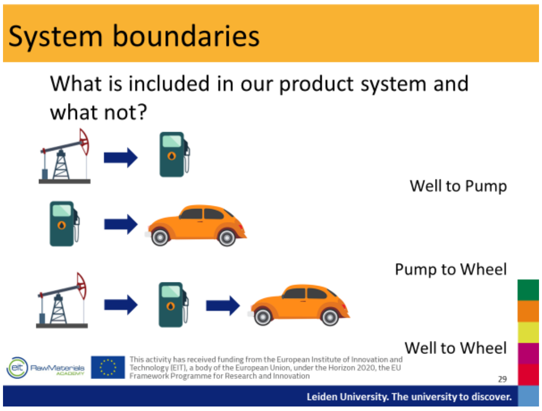
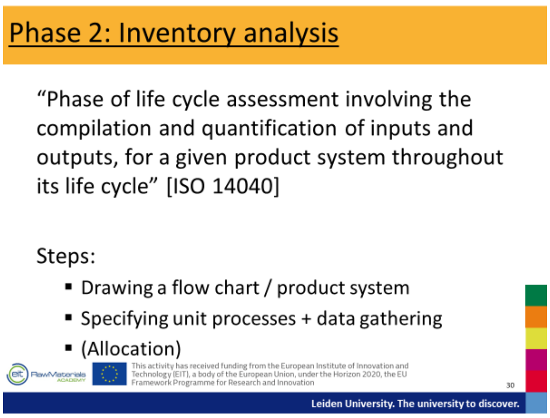
FU for a car?



What is the function of a container of milk?



How would you compare alternative vehicles? How about the number of kms driven for a certain lifetime?

	But an interesting thing is where exactly do you set your system boundaries? This is something that might come out of the scope definition in the GSD but will most probably be decided upon using some interplay between inventory and GSD phase. Here you see two options for setting the systems boundaries, for an LCA on newspapers: 1) you can start with the wood, and end with the discarded newspaper 2) you can start with a production forest, and end with a controlled dump site. Obviously, a real **cradle-to-grave** analysis suggests the second option. However, in some cases, an LCA-practitioner will still exclude certain processes from the product system (i.e., place them outside the system boundaries), for instance when time is limited, when data are too uncertain, etc. In any case, the system boundary should be explicitly discussed and clearly documented.
	What would you include in a product system of oil?
	Here is the definition of this phase, this is an ISO definition.

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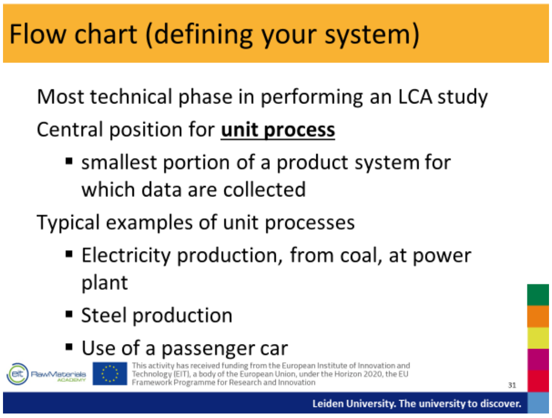
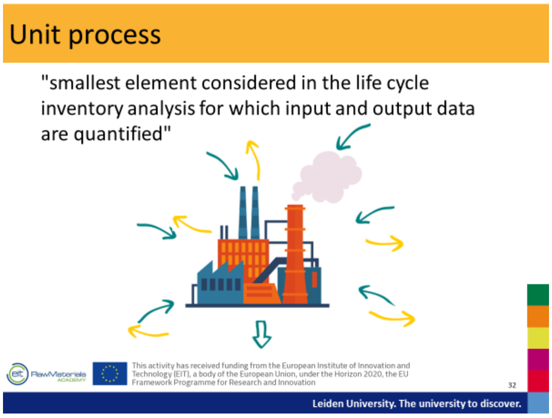


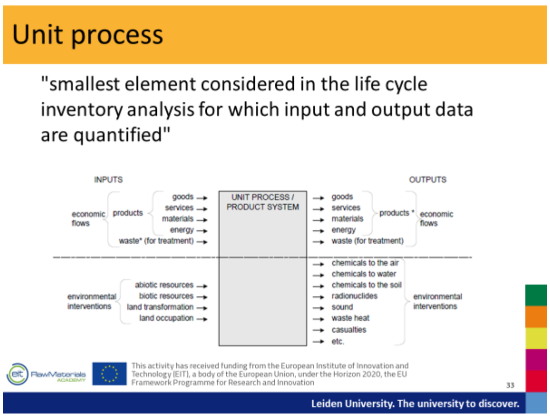
It is instructive to extend this list of examples in different directions. For instance:

1) potato cultivation
2) refining oil
3) watching a TV program
4) transporting materials by vessel
5) constructing a car
6) repairing a car
7) cleaning a car
8) dumping waste on a landfill
9) incinerating plastic waste with energy recovery

This list may be extended, preferably with examples for the specific target audience



The unit process is defined in ISO. This is the basic building block of an LCA system.



Inputs (economic and natural) and outputs of unit processes are documented in LCI.

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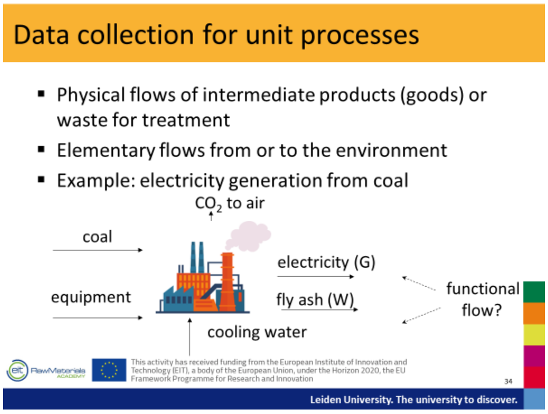
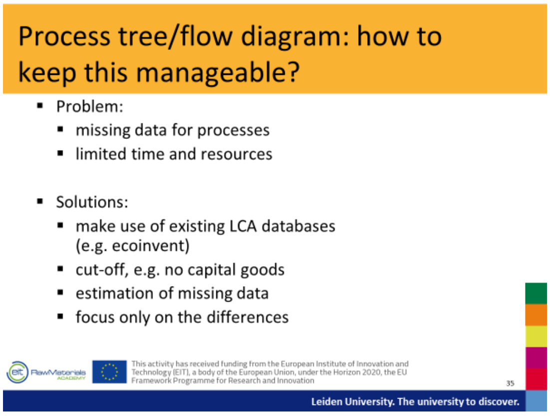


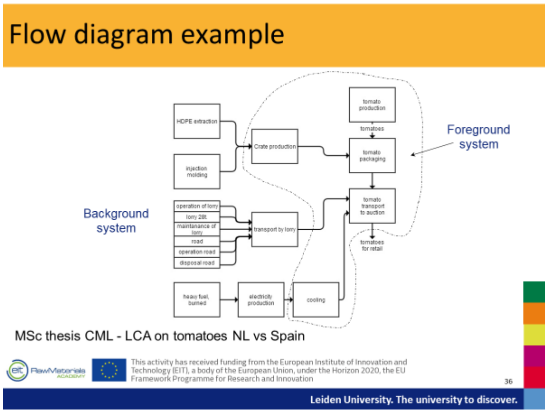
Unit processes are the core of LCI. It is of paramount importance to explain the idea.

Stress the distinction between process and flow, between intermediary flow and elementary flow, and between inflow and outflow.

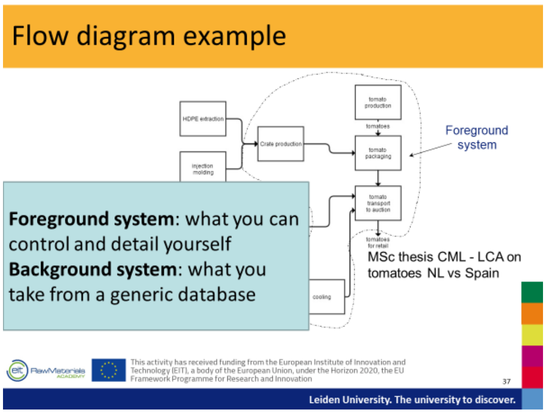
Different to a chemical process!!!



Where should you stop? This decision is linked to data availability. How much data do we have to assess at hand? How much access to we have to the function of the system. Here we show some solutions.



You see here an example from a MSc at CML in Leiden Uni. One can distinguish between a foreground system, i.e. the system of unit processes that are key to deliver the function of the system, and a background system, the system of collateral unit processes such as electricity production, extraction of materials, etc. The latter are typically not modelled directly by the analyst conducting the assessment, but are extracted from existing standard LCA databases (such as ecoinvent).



Here is a basic distinction between background and foreground.

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Calculation procedures

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38
Leiden University. The university to discover.

The calculation of results is of course an important thing in LCA. Nevertheless, it tends to be forgotten a bit in some textbooks, and usually, LCA software has hidden it as well. It concerns 2 distinct actions:

1) process data must be rescaled so as to satisfy the functional unit. For instance, when the product needs 12 kg plastic, and process data are given per 1000 kg of plastic, these data must be rescaled by a factor 12/1000.
2) the results are emissions and resource extractions specified per unit process. These are added across the processes in the second step.

In addition, step 1) may be problematic when some processes are multiple processes, such as combined power-heat production and coproduction of chlorine and sodium hydroxide. This problem must be explicitly solved in the allocation step.

More detailed information on rescaling and allocation is in module d.

Calculation procedures

- Relate process data to the functional unit (scaling)
- Aggregation over all unit processes in the inventory table
- Done usually by software using matrix algebra

Allocation of impacts over multiple functional flows (multiple outputs, multiple inputs, re-use and recycling).

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39
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The calculation of results is of course an important thing in LCA. Nevertheless, it tends to be forgotten a bit in some textbooks, and usually, LCA software has hidden it as well. It concerns 2 distinct actions:

1) process data must be rescaled so as to satisfy the functional unit. For instance, when the product needs 12 kg plastic, and process data are given per 1000 kg of plastic, these data must be rescaled by a factor 12/1000.
2) the results are emissions and resource extractions specified per unit process. These are added across the processes in the second step.

In addition, step 1) may be problematic when some processes are multiple processes, such as combined power-heat production and coproduction of chlorine and sodium hydroxide. This problem must be explicitly solved in the allocation step.

More detailed information on rescaling and allocation is in module d.

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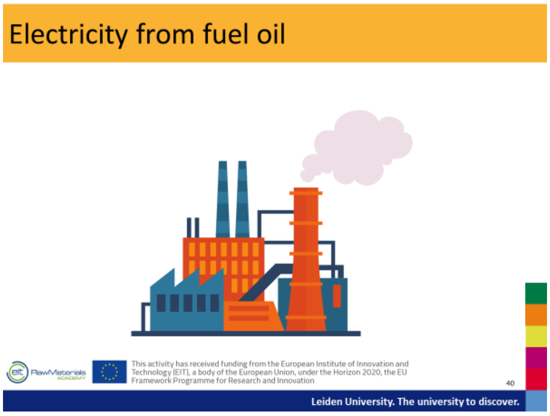
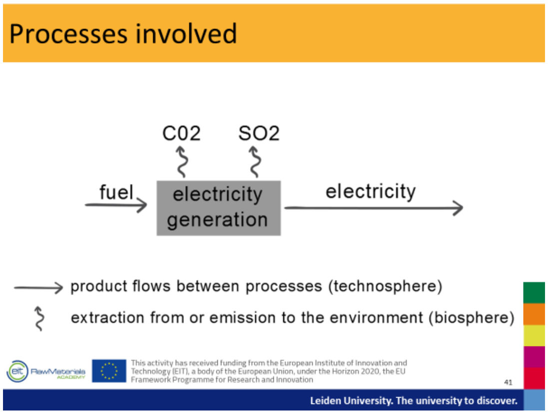
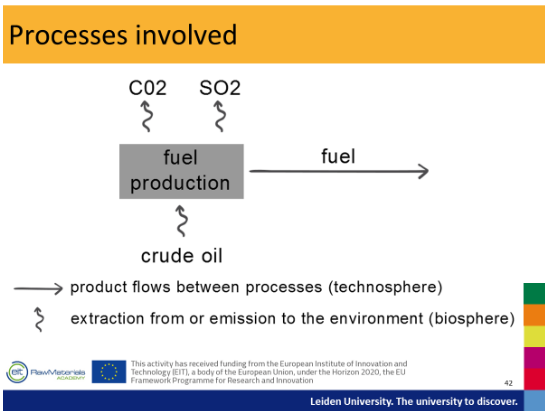


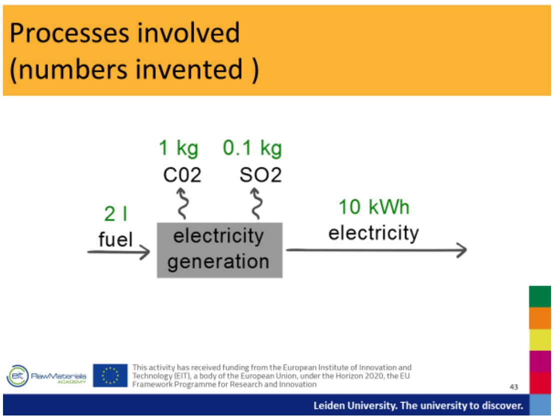
Let us study a simple example, and assess a system that should produce electricity from fuel oil.



We take into account a system of simple inputs and outputs. See the representation here.



Here you represented the fuel production process. There is one input: crude oil. Two chemical substances are emitted, CO2 and SO2. The output is fuel.



We need 2 litres of fuel to produce 10 kWh of electricity. There processes emit 1 kg of CO2 and 0.1 kg SO2.

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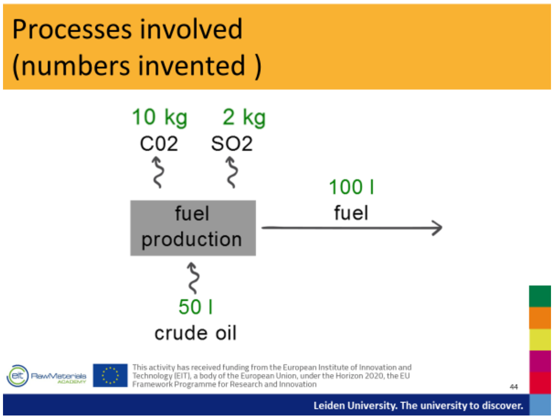
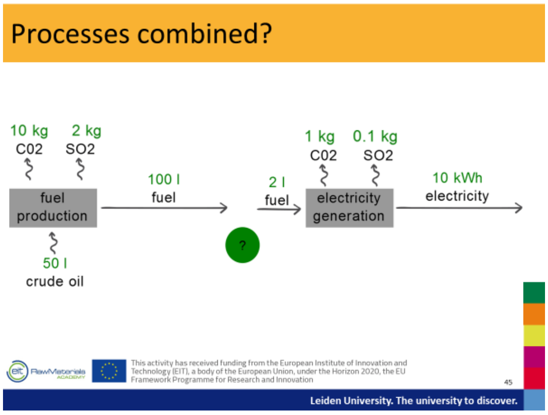
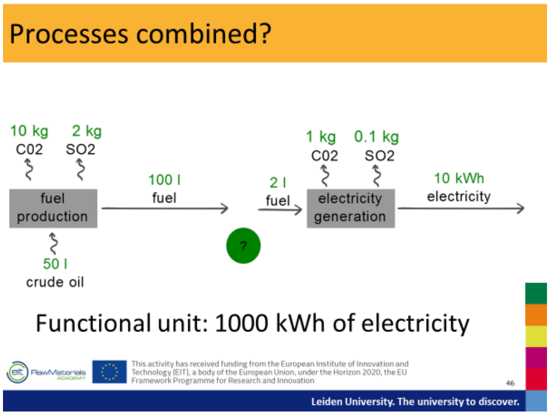


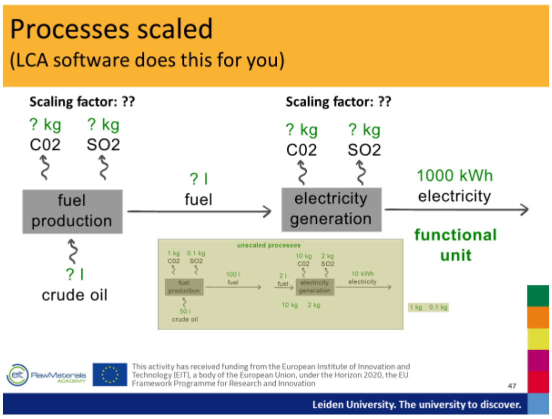
Similarly, we can define the production of fuel oil. 50 litres of crude oil are needed to produce 100 litres of fuel.



Let's considered these simplified processes combined. How would you combine them?



Let us consider as a functional unit for this system the production of 1000 kWh of electricity. We need then to scale this system.



In practice, LCA software would do this linear scaling for you. Scaling factors are needed to align fuel production to electricity generation.

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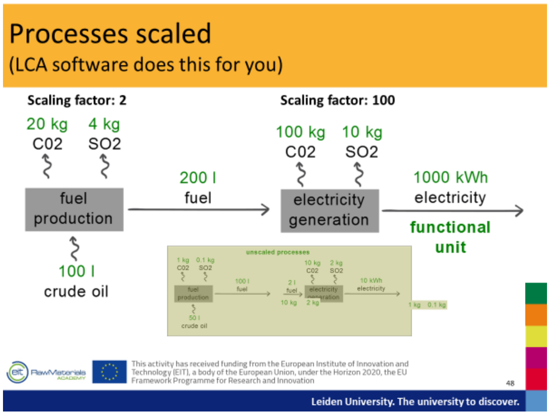
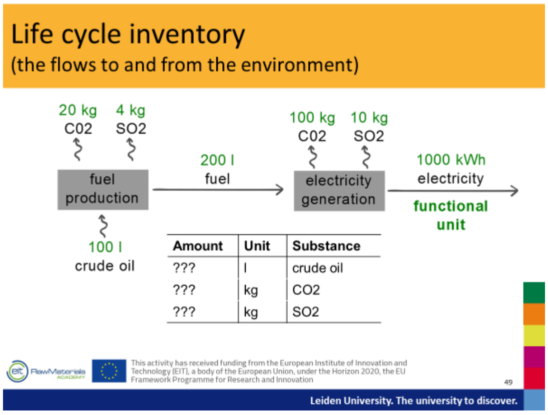
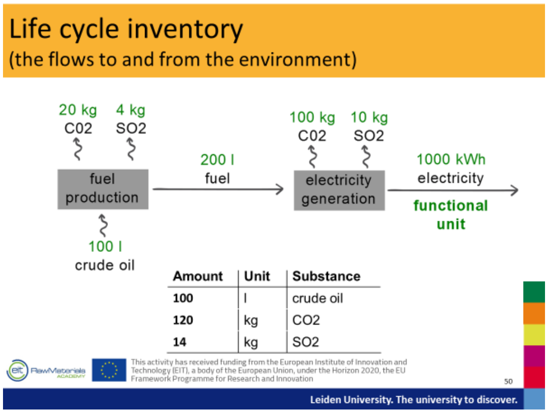


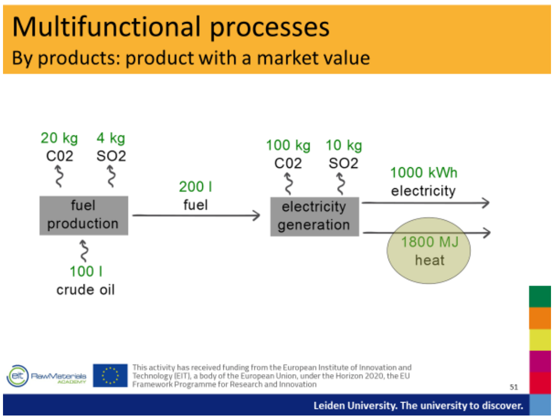
Here you see the calculated scaling factors for the system. 200 litres of electricity are needed to produce 1000 kWh of electricity. How would these numbers change if you'd produce 10000 kWh? Does the linearity assumption make sense?



Let us take a look at the emission side of things. What happened to the emissions? These were also scaled following from the functional unit going up to the fuel production.



In the table below we see all substances aggregated. Take a look at the units as well.



In real LCA studies it can happen that unit processes have more than one output. In our simplified example, let us assume that electricity generation is used not only to produce electricity but also heat, 1800 MJ of heat.

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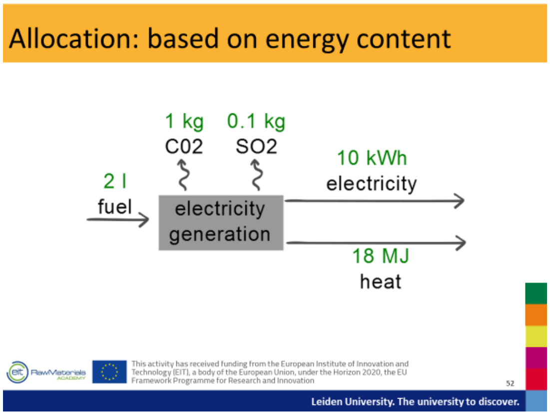
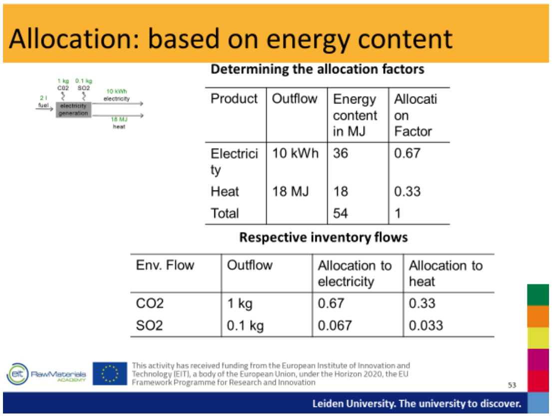


Processes are seldom producing just one single economic output. Consider this system producing electricity and heat. A number of methodological procedures are considered in the standard LCA practice to deal with such multi-functional processes. These include, for instance, the use of allocation rules based on the energy content, the physical or economic relationships among the connected subsystems.



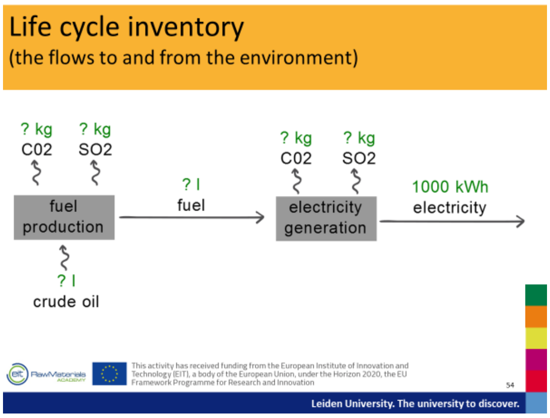
Determining the allocation factors

Product	Outflow	Energy content in MJ	Allocation Factor
Electricity	10 kWh	36	0.67
Heat	18 MJ	18	0.33
Total		54	1

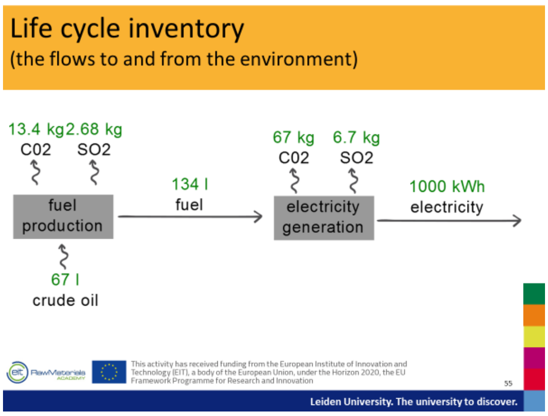
Respective inventory flows

Env. Flow	Outflow	Allocation to electricity	Allocation to heat
CO2	1 kg	0.67	0.33
SO2	0.1 kg	0.067	0.033

Here you see allocation factors calculated based on a variety of principles.



System unsolved.



Here's our system solved using our allocation rule.

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<table>
<tr>
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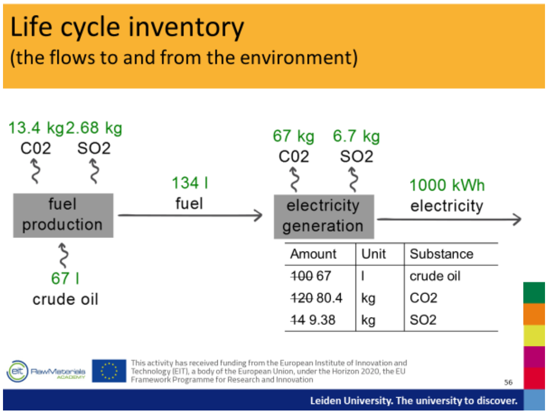

</td>
<td>See the updated table below.</td>
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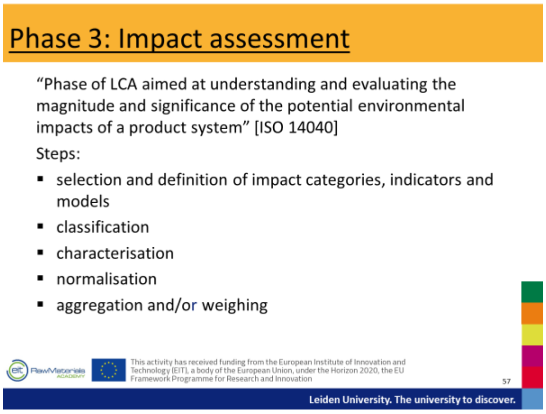

</td>
<td>Here is the definition of this phase, This is an ISO definition, and the steps listed are also those of ISO.

Translates interventions between system and environment in environmental impacts (mid point – end point?)</td>
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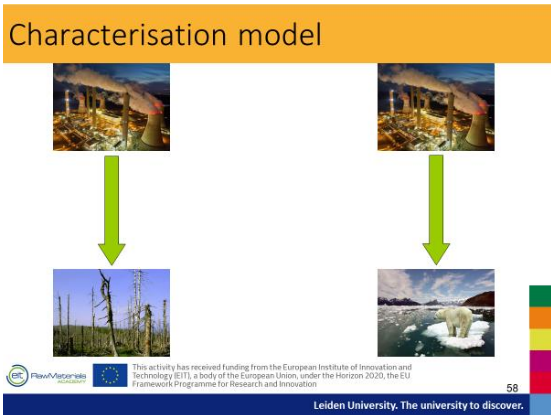
<tr>
<td>


</td>
<td>This shows a graphical idea of an environmental impact pathway: from stressor (top) to endpoint (bottom) via a number of Intermediate variables.

ISO14042

Mid point and end points</td>
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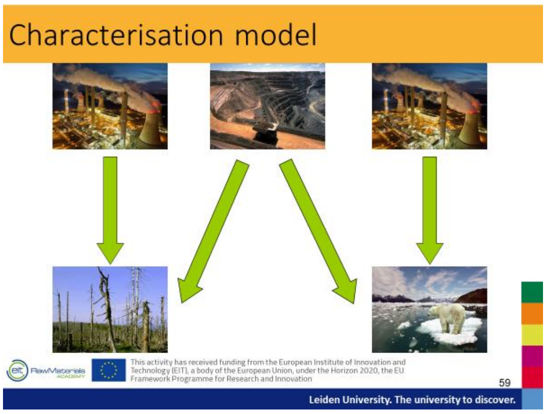

</td>
<td>This shows a graphical idea of an environmental impact pathway: from stressor (top) to endpoint (bottom) via a number of Intermediate variables.

ISO14042

Mid point and end points</td>
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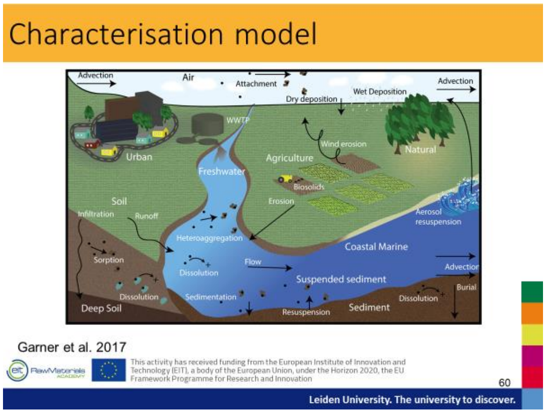
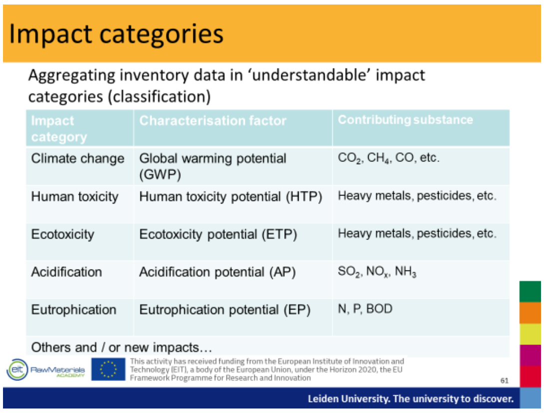
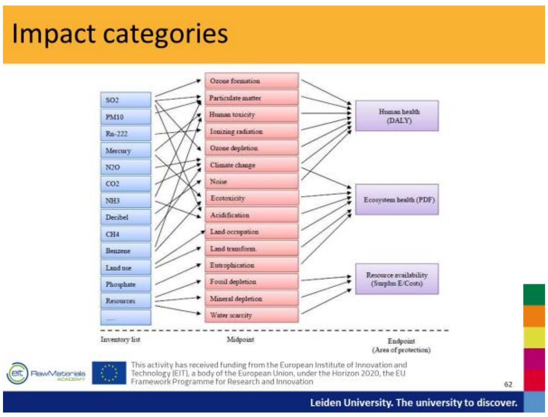


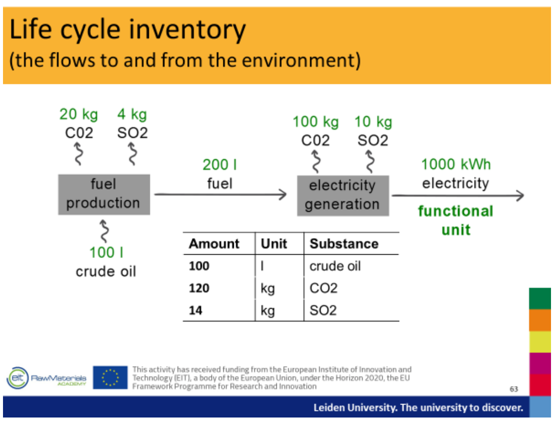
This is a graphical representation of how a characterization model for toxicants may work. Weather patterns, type of soils and media are considered, as well as the physical properties of the emitted substance. All of those are taken into account to calculate so-called characterization factors. Such factors allow characterizing specific impacts.



Between characterization factor and contributing substance is a characterisation model. Such models allow characterizing impacts across a variety of categories, such as climate change (the basis for the carbon footprint) and other categories, such as ecotoxicity. Various substances can contribute to one or multiple impacts.



Some characterization methods provide an aggregated impact score, along areas of protection: human health, resources, biodiversity. Aggregation rules allow to move from midpoint to endpoint.



Remember the table we calculated earlier on.

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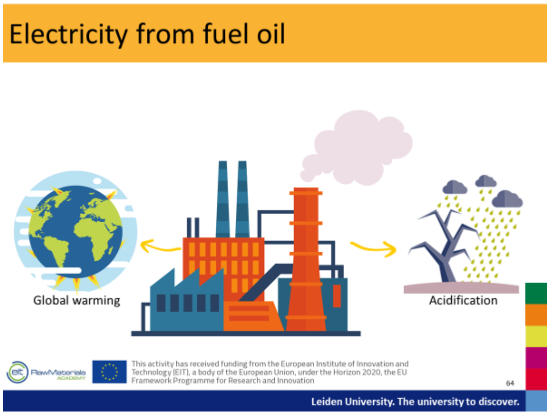
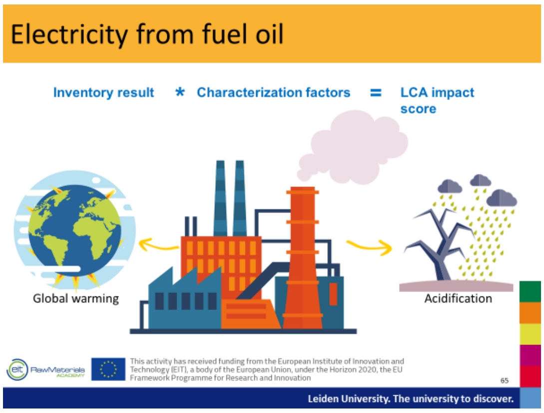
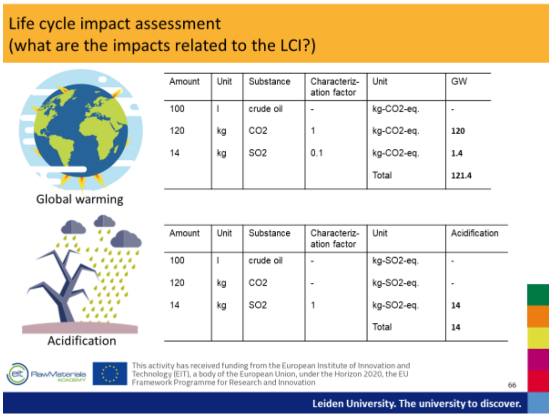


Let us take a look at how we would calculate impacts on climate change/global warming and acidification.



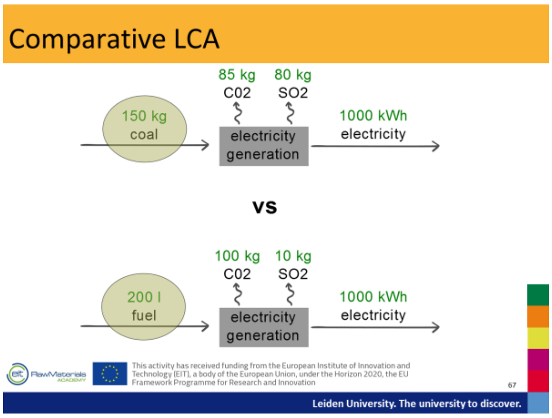
We simply multiply the results of the inventory table by the characterization factors that were modelled by expert groups for each relevant impact category. The result is an impact score.



Amount	Unit	Substance	Characteriz-ation factor	Unit	GW
100	l	crude oil	-	kg-CO2-eq.	-
120	kg	CO2	1	kg-CO2-eq.	**120**
14	kg	SO2	0.1	kg-CO2-eq.	**1.4**
				Total	**121.4**

Amount	Unit	Substance	Characteriz-ation factor	Unit	Acidification
100	l	crude oil	-	kg-SO2-eq.	-
120	kg	CO2	-	kg-SO2-eq.	-
14	kg	SO2	1	kg-SO2-eq.	**14**
				Total	**14**

Here you see the calculated results for the two selected impact categories.



Often LCA studies compare alternatives (see examples). Both assessed using the same functional unit.

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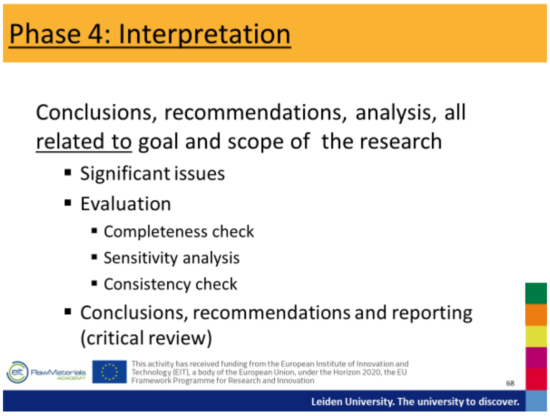
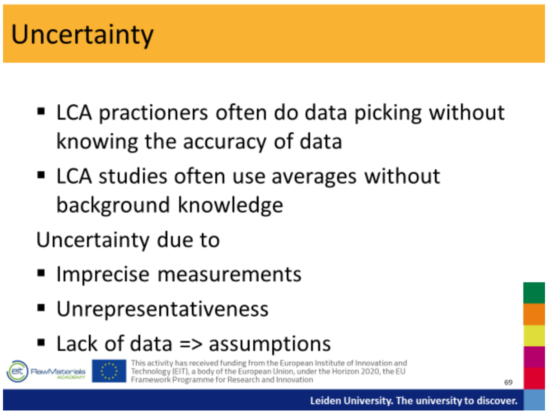


The final LCA phase in the ISO framework is the interpretation. Even when no impact assessment is done, you should go from the inventory analysis to the interpretation. Without interpretation, making conclusions and recommendations is dangerous.

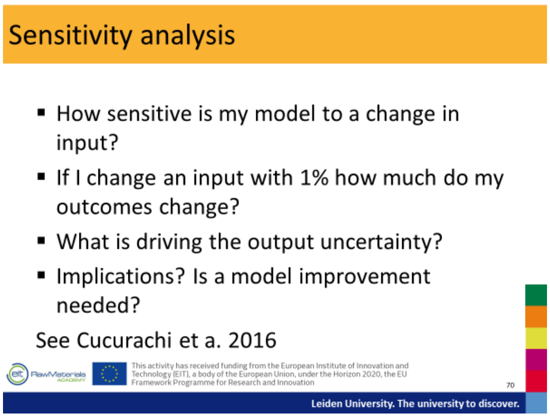
Below, we will give two examples:

1) contribution analysis
2) uncertainty analysis

There are, however, more techniques useful in interpretation.



Uncertainty is a key phase of LCA. Here you see why this is important.



Sensitivity analysis allows assessing the importance of individual inputs to outputs.

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Limitations of LCA What about… ▪ product level vs. global level? ▪ environmental impacts vs. economic and social impacts? ▪ static vs. dynamic? ▪ linear scaling? ▪ consequences of changes? ▪ geography and time? This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 71 Leiden University. The university to discover.	Also see handbook of LCA Guinée et al. (2002) page 42.
References ▪ Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. and Klüppel, H.J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment*, *11*(2), pp.80-85. Introduction to the standard practice of LCA. ▪ Guinée, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. *The international journal of life cycle assessment*, *7*(5), p.311. The Handbook provides a practical description of the ISO standard for LCA, the basics principles and the phases of LCA. ▪ Hellweg, S. and i Canals, L.M., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science, 344(6188), pp.1109-1113. State of the art LCA practice, trends and new developments. This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 72 Leiden University. The university to discover.	
LIFE CYCLE ASSESSMENT STEFANO CUCURACHI, LEIDEN UNIVERSITY, CML This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation ©Leiden University, 2019	

3 Exercises on LCA of neodymium agents

Below the description of the exercise. Additional calculation files and results are supplied in .xlsx format.

Hypothetical case study: Production of 1 kg of NdFeB magnet

INTRODUCTION

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In this exercise you will perform a highly simplified LCA. The main goal of this assignment is to improve your understanding of the LCA methodology, into how it works and into what it involves.

Most of you will not have worked with LCA before. This is not a problem: you just have to read the exercise carefully and discuss it with your fellow students, and if you are still in doubt, ask the instructor for further explanation. You can do this exercise together with other students (2–3).

The subject of the case study is the production of 1 Kg of NdFeB magnet. This quantity corresponds to the average quantity that needs to be used to support the functioning of an electric vehicle. You will not be performing a complete LCA study, but will merely look at a simplified system of processes, and at a few types of emissions, and impact categories.

The description below will guide you through the calculations step-by-step.

The results and all other methodological issues will be discussed with the whole group at the end of the practicum.

GOAL AND SCOPE DEFINITION

The functional unit for this simplified LCA is '1 kg of NdFeB magnet to support the functioning of an electric vehicle for 20 years'. For the sake of simplicity, you will not be doing a comparative LCA, although in the final interpretation phase of the exercise you will be asked to reason on the differences between the current system you analysed and the potential comparison with one or multiple alternatives.

INVENTORY ANALYSIS

Process flow diagram and process data

The process flow diagram for the system you will study is depicted in the figure below. The system consists of a number of processes that are needed to produce NdFeB magnets. As shown during the lecture, the processes highly simplify the reality of manufacturing magnets. But that's not a problem for now. These processes are:

- Mining
- Mine construction
- Landfill

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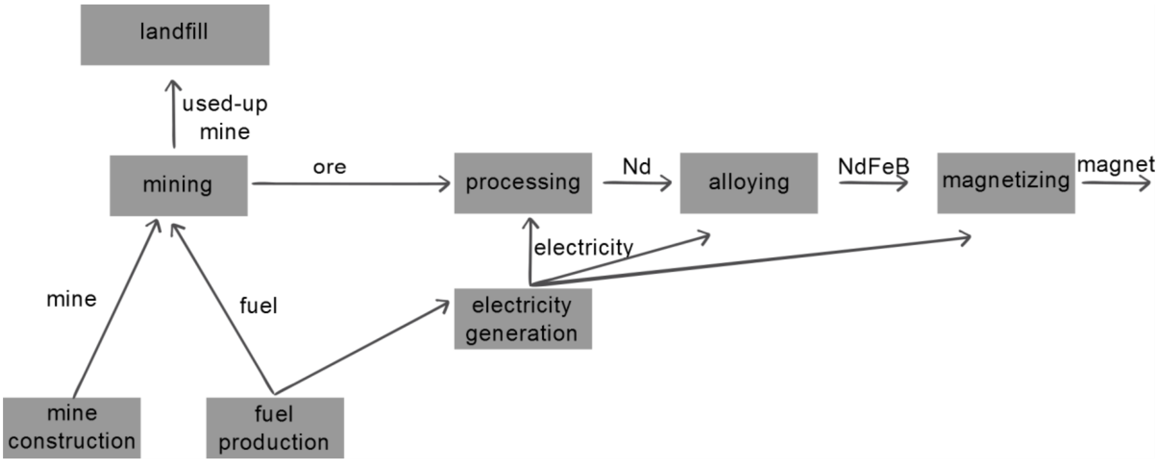
- Fuel Production
- Electricity generation from fuel
- Processing of REO ore
- Alloying of NdFeB
- Magnetizing of NdFeB

Process data for these processes, including economic inflows, economic outflows, environmental resources, and environmental emissions are reported in the excel file 'data_for_practicum_simple_final.xlsx'.



Assignment – 1. Flow diagram and process data

Consider the flow diagram depicted above and take a look at the process data in the excel sheet 'data_for_practicum.xlsx'.

a) How do the two relate?

b) How does the simplified flowchart relate to the real process of manufacturing of magnets?

Assignment – 2. Scaling processes and emissions

As we have seen in the lecture, process data is not necessarily scaled to the final functional unit, or to intermediate reference flows. Scaled processes are needed also in the later phase of the study when impacts need to be quantified across the full life cycle.

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a) Consider the process data and proceed with scaling all processes to the functional unit. You can do this by hand or directly in the excel sheet provided

b) Report all scaled value on the flowchart printed above

Assignment – 3. Compiling inventory table

Once all processes have been scaled, compile all the necessary information in an inventory table.

c) Report in the inventory table all scaled environmental, and economic inflows and outflows.

Use the format below

Item	Quantity	Unit
....	--	--

IMPACT ASSESSMENT

Assignment – 4. Calculating impacts

During the classification phase of LCA, environmental inflows and outflows are assigned to impact categories. For the sake of simplicity and time, all environmental inflows and outflows are already classified to impact categories, and the related characterization factors are reported in a separate table.

d) Please calculate the impact scores for all impact categories. Once again you may use Excel or do it by hand.

Assignment – 5. Contribution analysis

Consider the impact scores.

e) Which process contributed the most to each impact category?

INTERPRETATION

Assignment – 6. Interpretation

In the interpretation phase of LCA the analyst provide her final thoughts on how the system performed, the assumptions made, the sources of uncertainty in the data and the results.

f) What were the most surprising results in your opinion?

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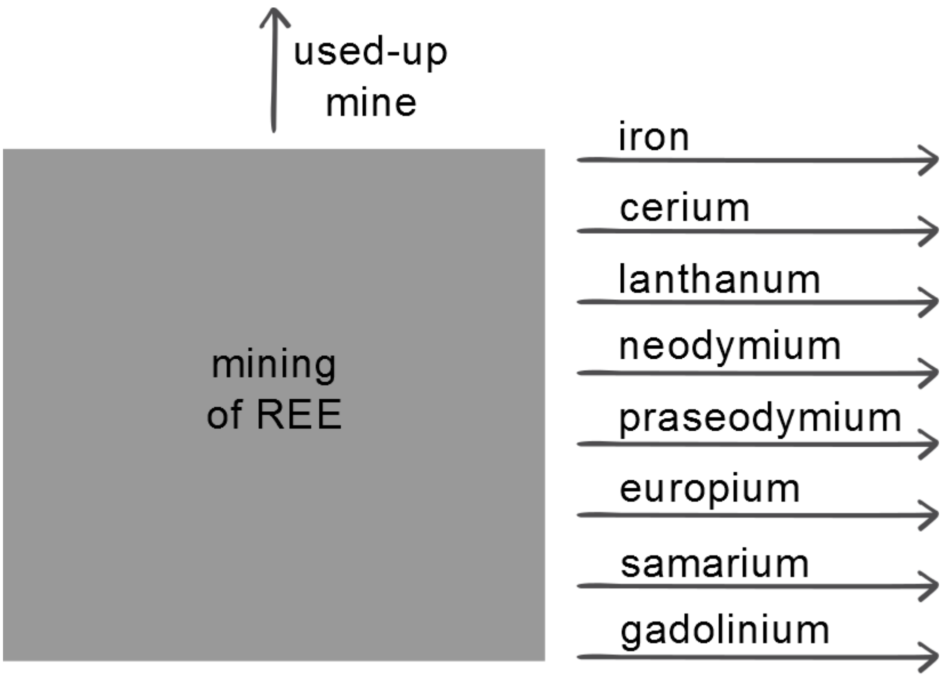
g) What would you do if you were to recommend a decision maker on how to improve the supply chain of NdFeB magnets?

FURTHER ANALYSIS - TAKEHOME

Assignment – 7. Allocation

We have considered an admittedly simple case that does not represent the reality of typical LCA case studies. We have so far limited the complexity, as there were no multi-functional processes in the system considered. All then went smoothly: no allocation, no pain.

Consider now the more realistic case that the process "mining of REE" is a multi-functional one and is defined as in the figure below.



The updated process data for the updated process "mining of REE" is reported in the excel sheet "mining_of_REE.xlsx". To make our lives easier, let us still focus on neodymium, so that we don't need to change too much in our calculations. Proceed as follows:

h) Plug the updated process "mining of REE" into the flowchart. What happens now?

i) All of the outputs of the process have an economic value. Look up on the internet the price per kg of each of the earths and metals extracted simultaneously from our simple

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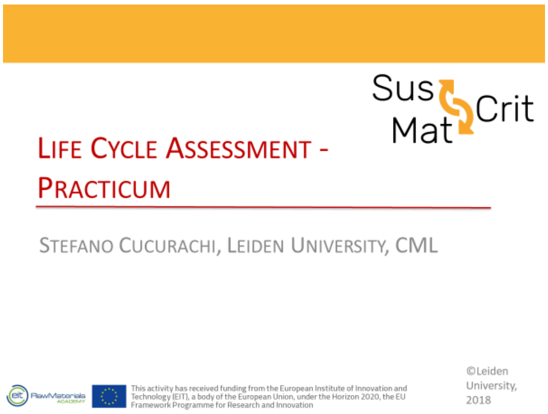
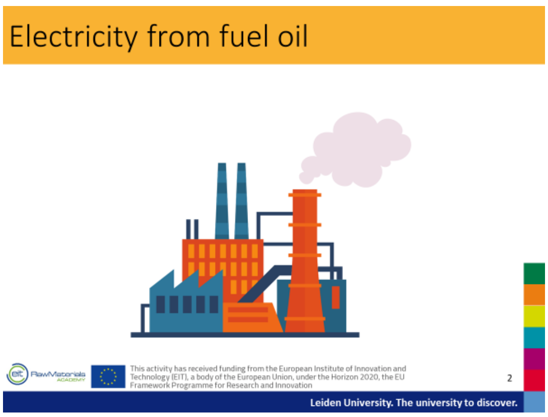
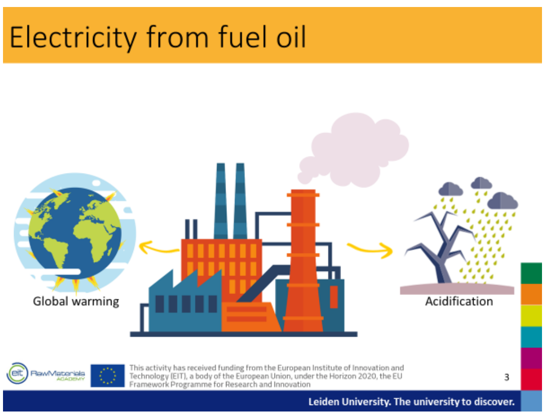
mine system. If you need to do assumptions to get to the price per kg, just note them down.

j) Proceed with an economic allocation of environmental resources and emissions based on the economic allocation of impacts. Still consider neodymium as our desired output. Do you need to update the scaling factors?

Re-calculate all impact scores and assess results.

Slides for the exercise:

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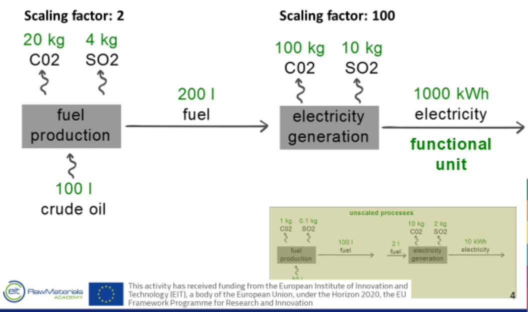
Processes scaled



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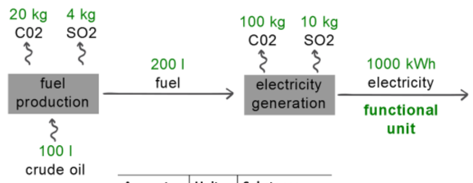
Life cycle inventory (the flows to and from the environment



Amount	Unit	Substance
100	l	crude oil
120	kg	CO2
14	kg	SO2

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Life cycle inventory (the flows to and from the environment

Global warming

Amount	Unit	Substance	Characteriz-ation factor	Unit	GW
100	l	crude oil	-	kg-CO2-eq.	-
120	kg	CO2	1	kg-CO2-eq.	**120**
14	kg	SO2	0.1	kg-CO2-eq.	**1.4**
				Total	**121.4**

Acidification

Amount	Unit	Substance	Characteriz-ation factor	Unit	Acidification
100	l	crude oil	-	kg-SO2-eq.	-
120	kg	CO2	-	kg-SO2-eq.	-
14	kg	SO2	1	kg-SO2-eq.	**14**
					14

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Process tree/flow diagram: NdFeB magnets

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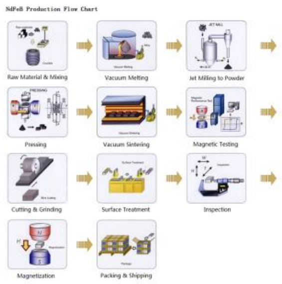
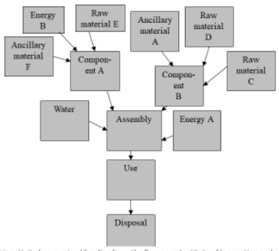
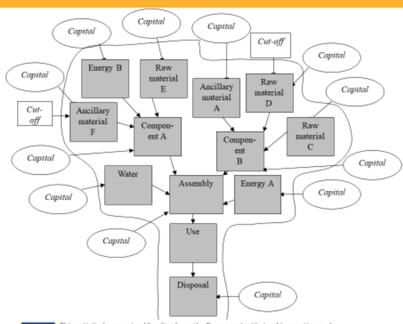
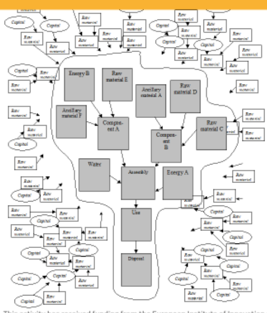
Process tree/flow diagram: NdFeB magnets  ndfebmagnet.net This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 8 Leiden University. The university to discover.	
Process tree/flow diagram: system boundaries and cut-off  Suh, 2009 This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 9 Leiden University. The university to discover.	
 Suh, 2009 This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 10 Leiden University. The university to discover.	
 Suh, 2009 This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation 11 Leiden University. The university to discover.	

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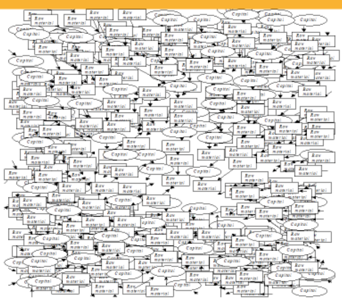

Suh, 2009

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12

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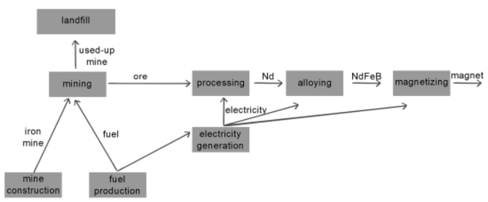
Process tree/flow diagram: NdFeB magnets



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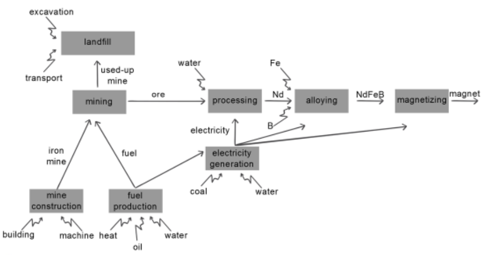
Process tree/flow diagram: NdFeB magnets



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Scaled processes

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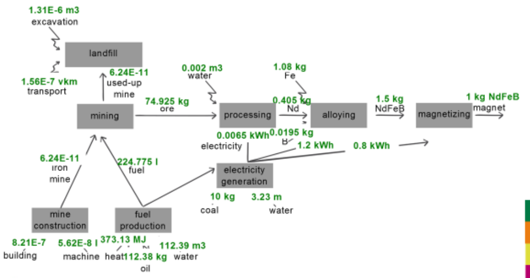
Scaled processes



16

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IMPACT ASSESSMENT

17

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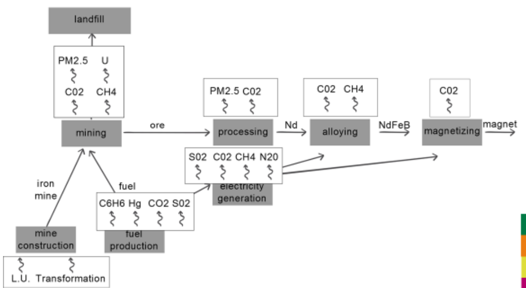
Process tree/flow diagram: NdFeB magnets



18

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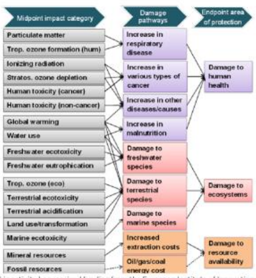
Recipe 2016



19

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Discussion of results

- What did we find?
- Interpretation?
- Demonstration in software

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LIFE CYCLE ASSESSMENT - PRACTICUM

STEFANO CUCURACHI, LEIDEN UNIVERSITY, CML

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4 Assessment Questions

No further questions is provided with this lecture, as the exercise already covers all the learning goals and the concepts introduced in the lecture.

5 Acknowledgements and Authors

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The following authors have contributed to prepare the complete teaching material kit and intend to provide an overview of major topics surrounding the sustainable management of critical raw materials:

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6 Citation

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7 Disclaimer

The teaching materials within the SusCritMat project have been prepared with great care and experienced several revisions. Nevertheless, the consortium assumes no liability for the topicality, completeness and correctness of the content provided.

In case you have suggestions or other feedback how to improve the materials, we value your opinion: Please contact us via the project webpage https://suscritmat.eu/contact/.

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