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DDI8003E – Week 7
Multifunctionality and recycling

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(content produced with contributions from Pr. Laure Patouillard and Pascal Lesage)

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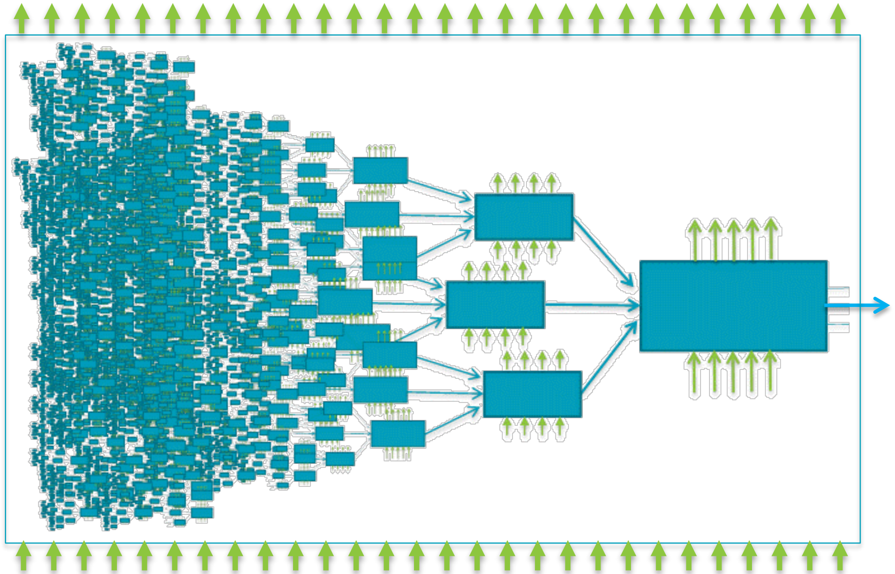
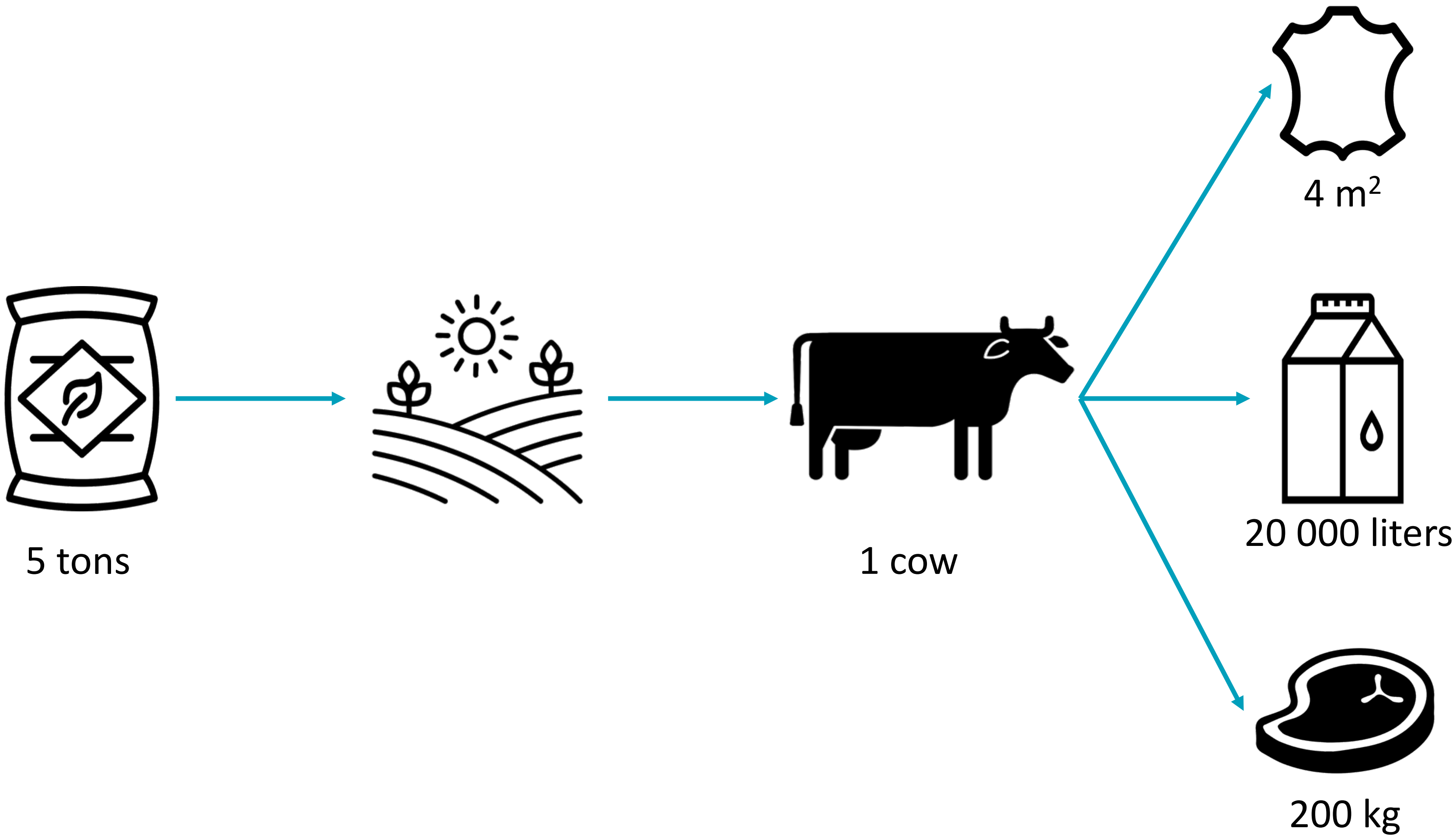
Recap: System boundary

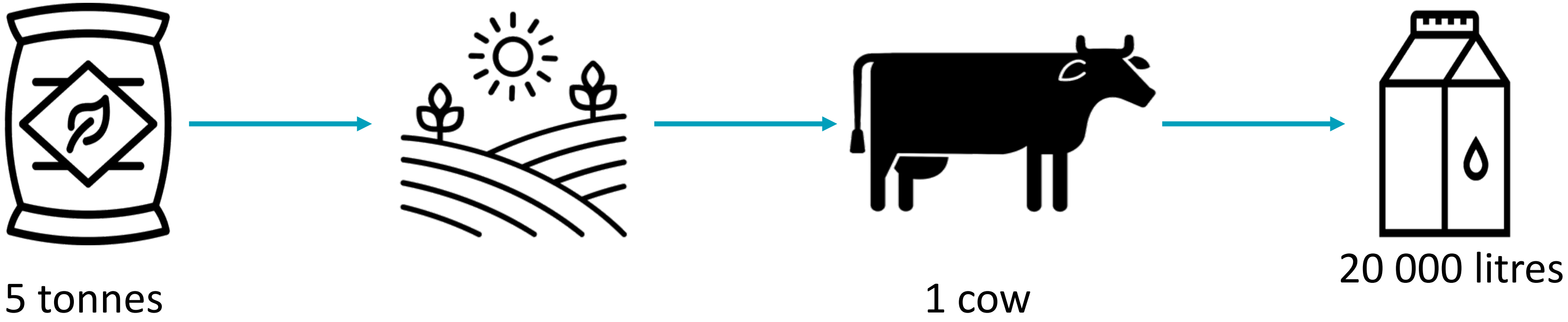
- In theory, the only economic flows that cross the system boundary in the study are directly associated to the function (**final demand flow**)
- The other economic flows are entirely consumed by the other unit processes (fundamental assumption: **market balance** assumption)
- All other flows that cross the system boundary are elementary flows



Multifunctional processes – the example of a cow

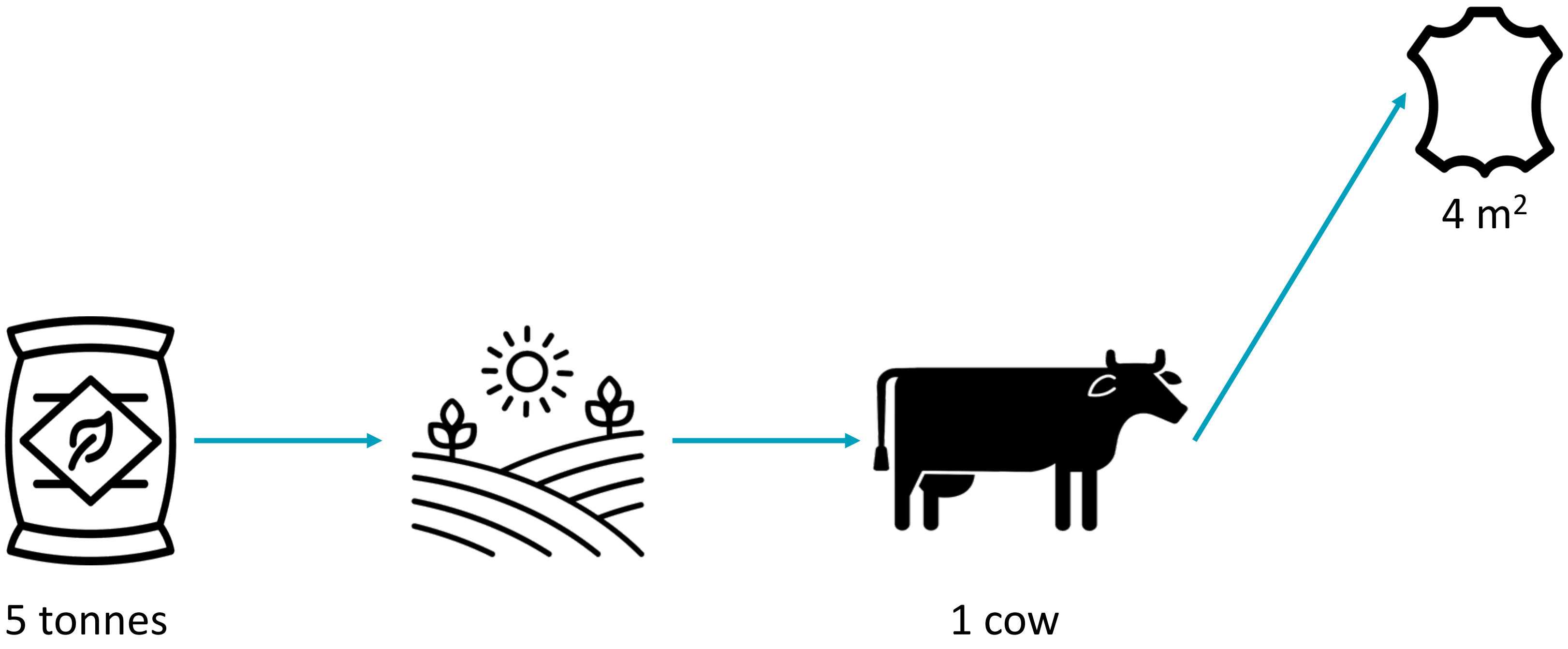


Multifunctional processes



5 tonnes of fertilizer for the milk

Multifunctional processes



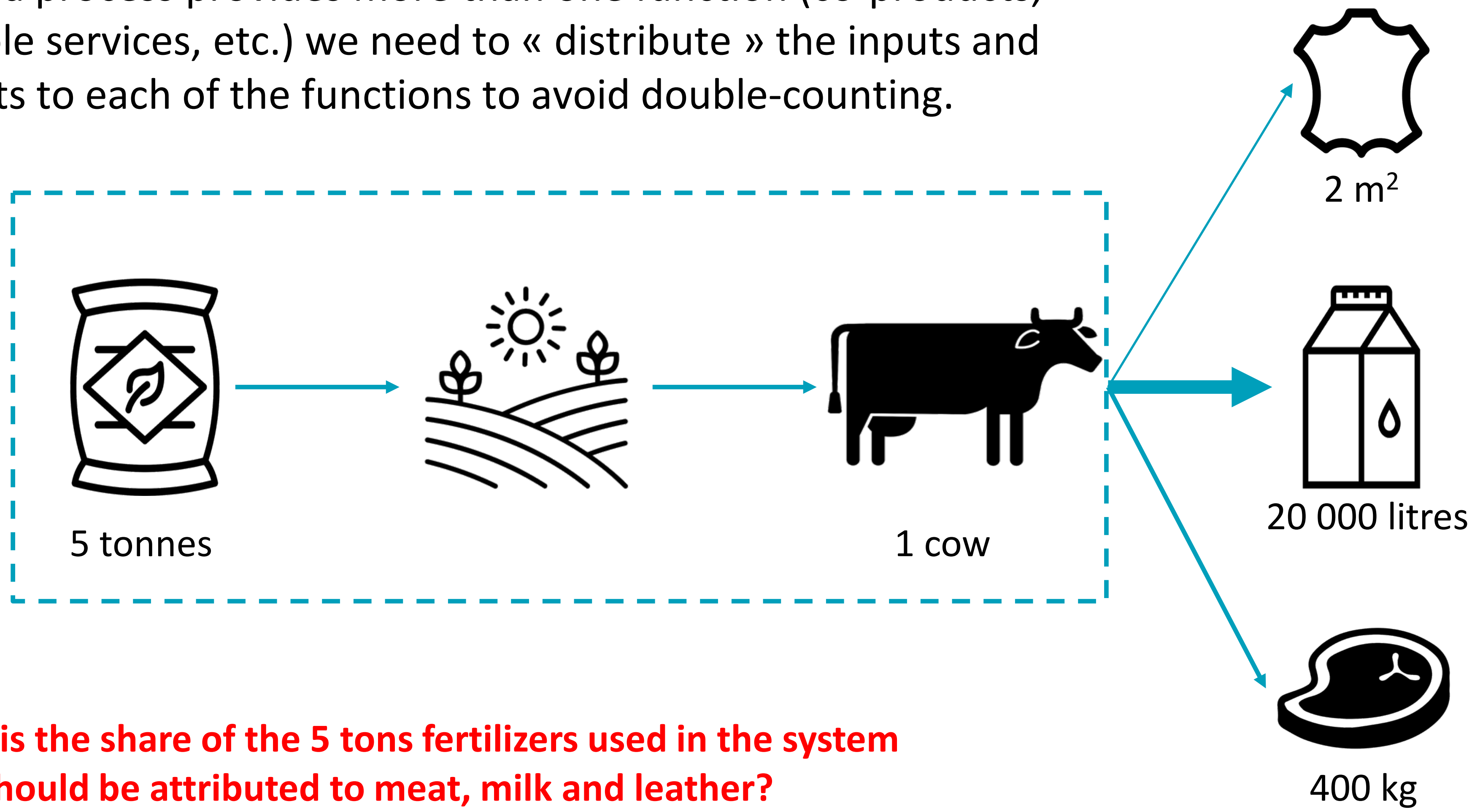
5 tonnes of fertilizer for the milk
+ 5 tonnes of fertilizer for the leather

Multifunctional processes

5 tonnes of fertilizer for the milk
+ 5 tonnes of fertilizer for the leather
+ 5 tonnes de fertilizer for the meat
= 15t!! → **ERROR! Double counting**

Multifunctional processes

- When a process provides more than one function (co-products, multiple services, etc.) we need to « distribute » the inputs and outputs to each of the functions to avoid double-counting.



What is the share of the 5 tons fertilizers used in the system that should be attributed to meat, milk and leather?

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Processus multifonctionnels

- Imagine the following situation: an almost deserted island is home to a field that can support a cow for the rest of her life.
- During this time, 5 tons of fertilizer were used. During her lifetime, the cow produces a few thousand liters of milk. At its death, 4 m2 of leather and a couple of hundreds kg of meat are produced.
- An LCA is performed on the milk produced. A process tree is used to identify the processes involved in applying the fertilizer as part of the product system.
  - **After calculation, it is determined that 5 tons of fertilizer are needed to produce the milk.**
  - **A second LCA is performed on the leather produced. Again, it is identified that the fertilizer application should be accounted for. After calculation, it is concluded that 5 tons of fertilizer are needed to produce the leather.**
- You make a simple addition, 5 tons + 5 tons = 10 tons of fertilizer. Now, you know, as the manager of the island, that you used 5 tons... Find the mistake.

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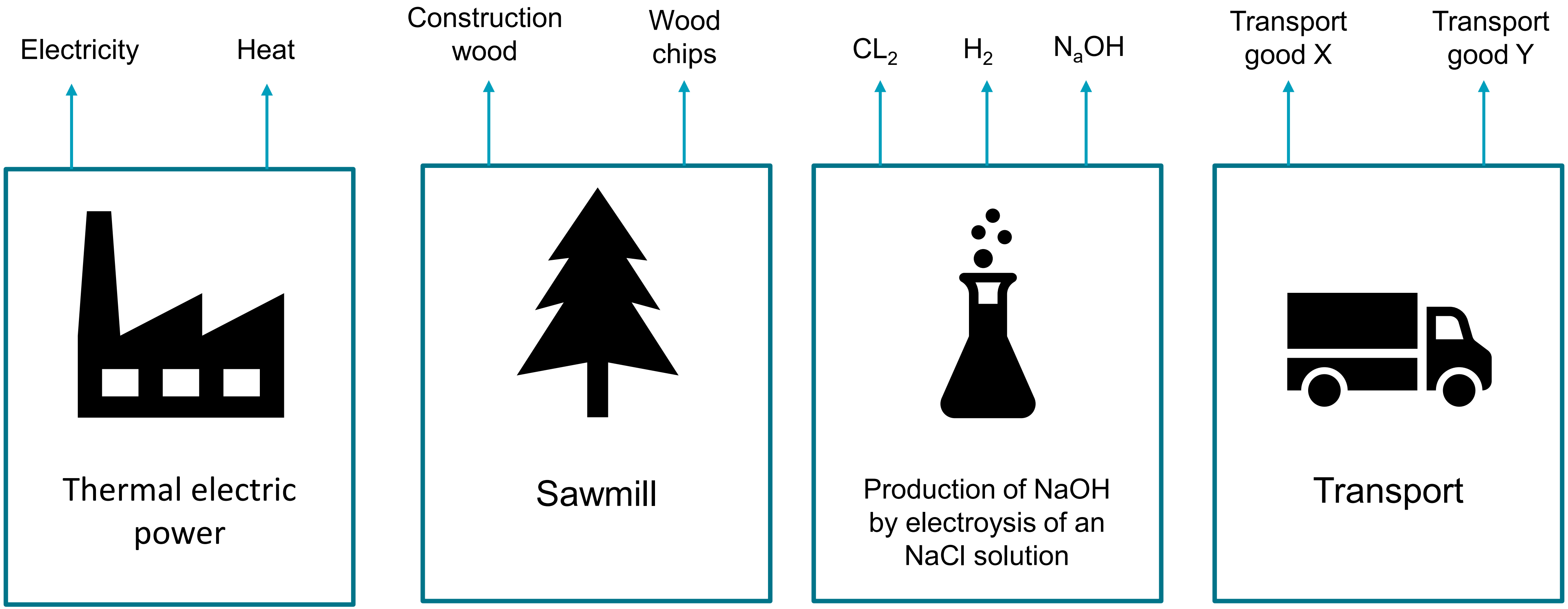
Multifunctional processes

- These processes are omnipresent:



Multifunctional processes

- Different levels of **technological linkage** between coproducts (are they always coproduced in the same ratio? Does the production of one force the production of the other?):
  - **Refining petroleum: jetfuel (aviation fuel), gasoline, diesel, propane, bitumen, etc.**
  - **Wheat cultivation: straw, wheat grain**
  - **Raising cows: meat, milk, leather**
  - **Thermal electric power plant: electricity, heat**
  - **Sawmill: construction wood, wood chips for paper production, wood waste for energy production**
  - **Production of NaOH by electroysis of an NaCl solution: NaOH, Cl_2, H_2**
  - **Transportation: many products transported in the same truck**

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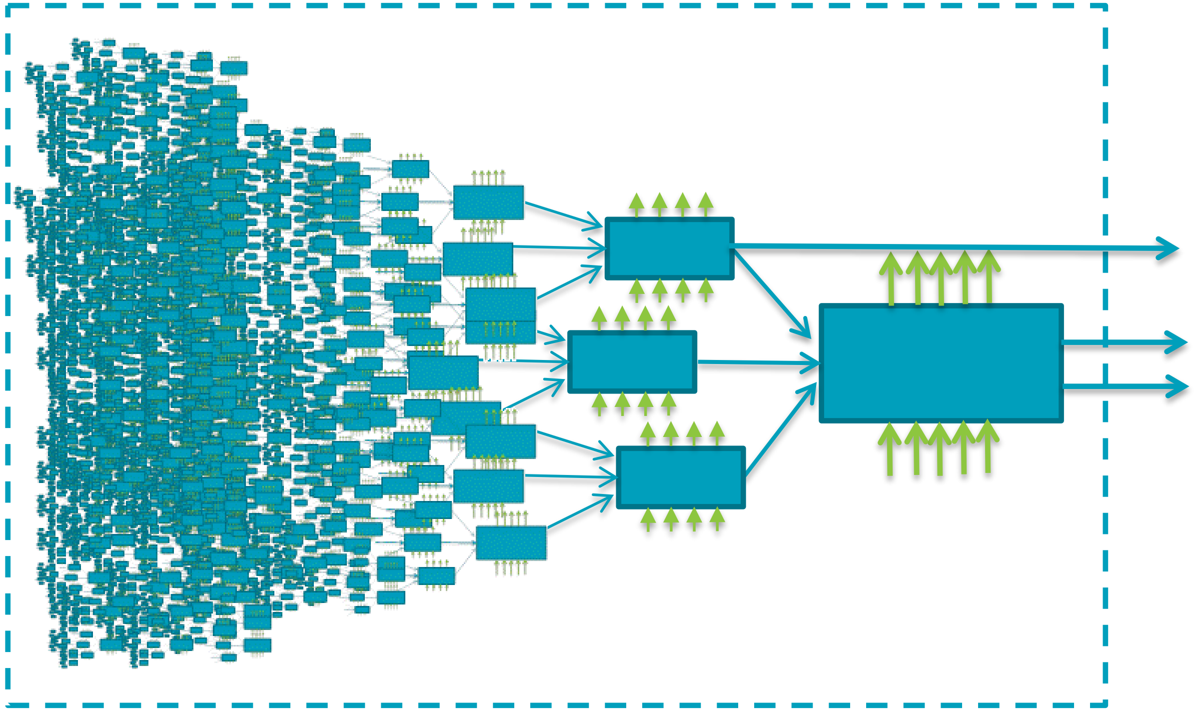
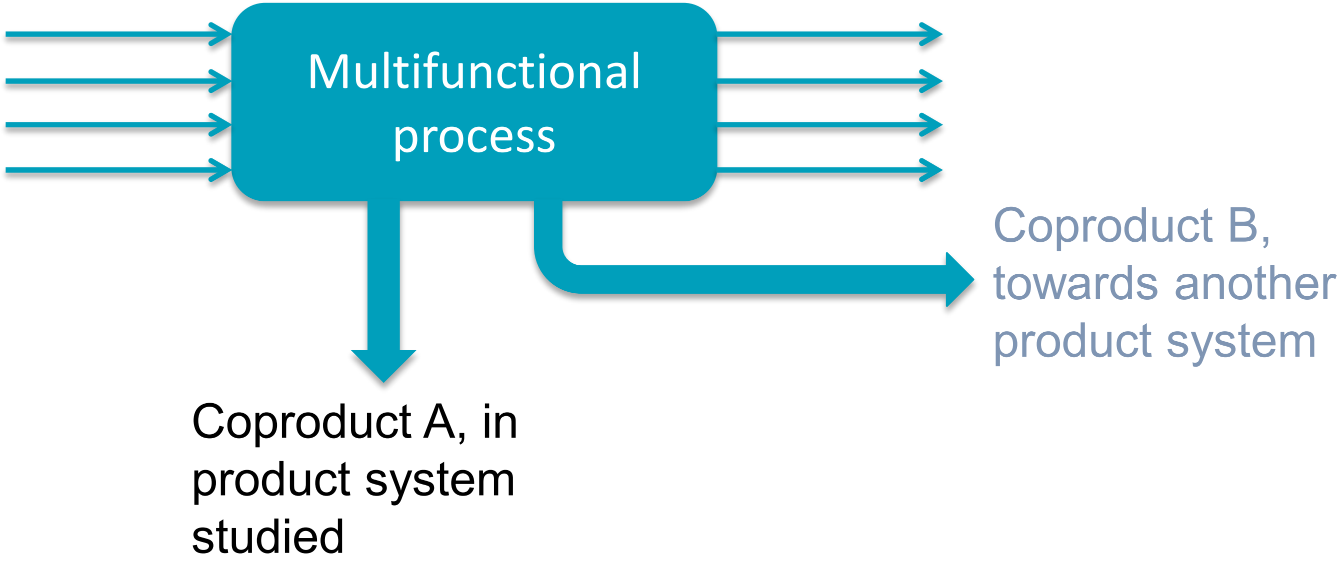
Why multifonctionality is a problem?

Problem of « double counting »

Only one intermediary flow can cross the system boundary



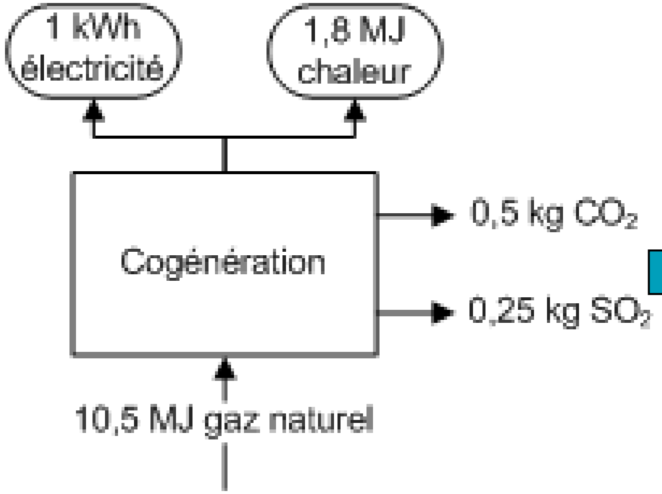
Multifunctionality problem

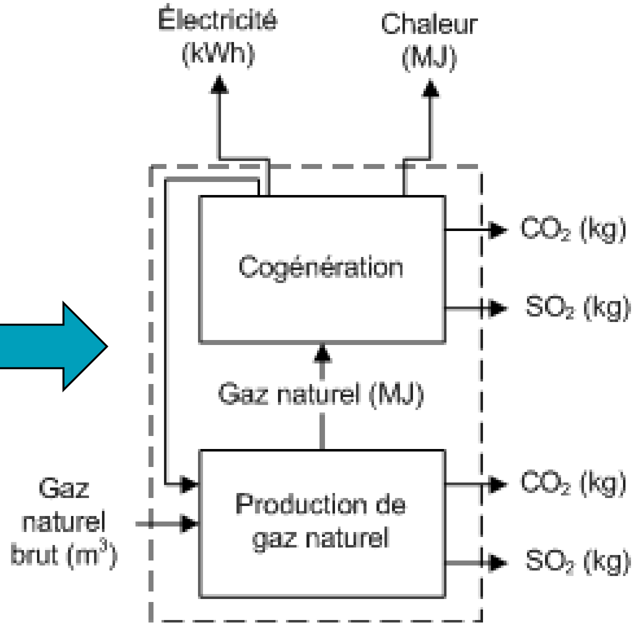


Problem: What proportion of impacts associated to the inputs and outputs of the multifunctional process should be attributed to coproduct A?

Multifunctional processes

- With multifunctional processes, more than one economic flows cross the system boundary: <u>the system has more than one function</u>
- With multifunctional processes, we will also have non-inversible **A** matrices (not square)…





	p_{cogen}	p_{GN}	
Electricity (kWh)	1	-2,5	A
Natural gas (MJ)	-10,5	1000	
Heat (MJ)	1,8	0	
Raw natural gas (m^3)	0	-25	B
CO_2 (kg)	0,5	10	
SO_2 (kg)	0,25	0,01	

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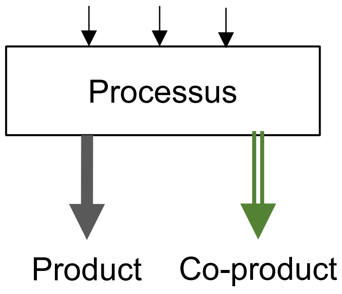
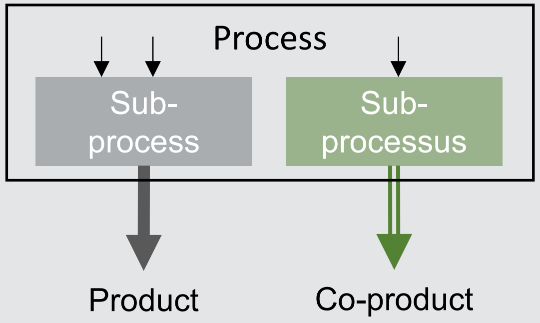
How to solve multifunctionality in LCA?

- Subdivision
- System expansion
- Allocation based on underlying physical relationship
- Allocation based on other relations

Overview of approaches to deal with multifunctionality

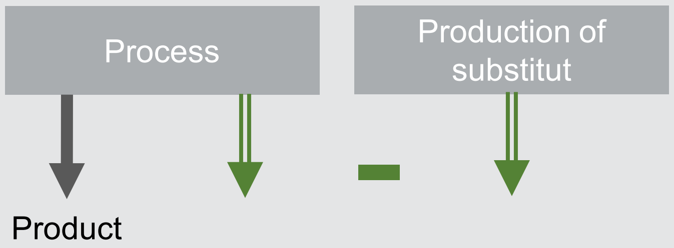


Subdivision

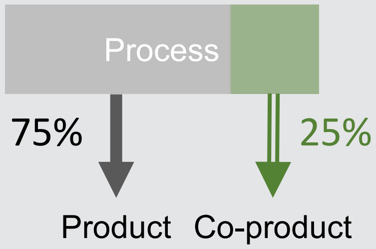


System expansion

Substitution



Allocation



- Allocation based on underlying physical relationship
- Allocation based on other relationship (economic, massic, energetic, etc.)

Patouillard, L., Maxime, D., Menard, J.-F., De Wachter, H., Greffe, T., & Bolay, A.-F. (2022). Analyse du cycle de vie de la biomasse énergie : état de l'art, enjeux méthodologiques et recommandations. SCORELCA.

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Multifunctional processes and ISO 14044

ISO 14044, section 4.3.4.2: The study must identify the processes shared with other product systems and follow the step-by-step procedure presented here:

Step 1: Avoid allocation as much as possible by:

- **Subdividing the unit process by creating two sub-processes or more**;
- **Extend the system boundary of the product system**

Step 2: Allocate the inputs and outputs in a way that reflects underlying physical relationships existing between them.

Step 3: Allocate inputs and outputs in a way that reflects other mutual relationships (mass, economic, etc.)

Multifunctional processes and ISO 14044

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- Subdividing Subdivision creating two sub-processes or more;
- Extend the System expansion t system

Step 2: Allocate the inputs and outputs in a way that reflects underlying physical relationships existing between then

Allocation – Underlying physical relationship

Step 3: Allocate inputs and outputs in a way that reflects other mutual relationships (mass, economic, etc.)

Allocation – Other relationship

ISO calls them steps, but they are in fact
4 mutually exclusive options ranked by priority order

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How to solve multifunctionality in LCA?

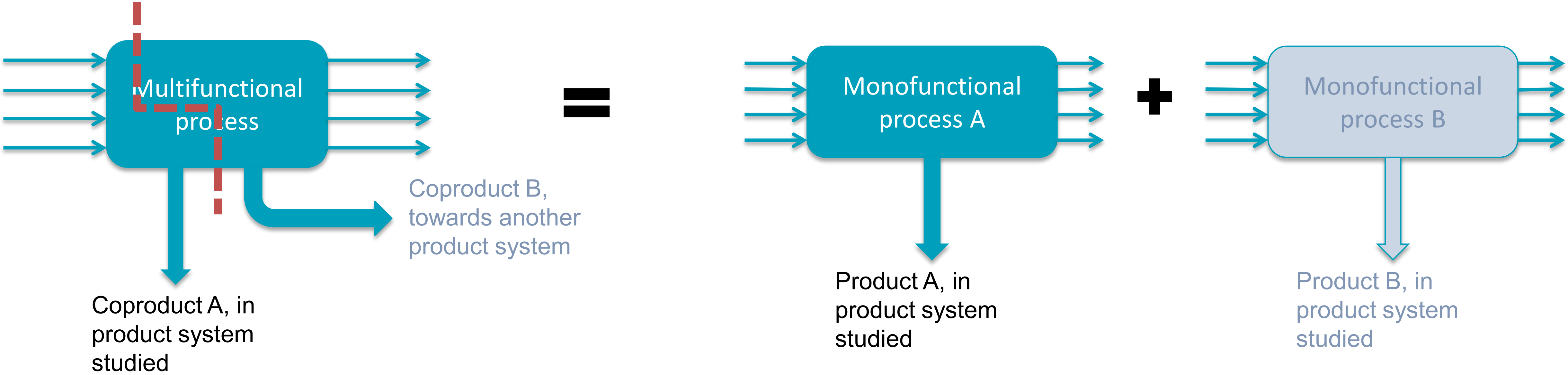
1. Subdivision

2. System expansion

3. Allocation based on underlying physical relationship

4. Allocation based on other relations

ISO 14044 Procedure– Step 1a: Subdivision



Step 1.1: Divide the process in sub-processes

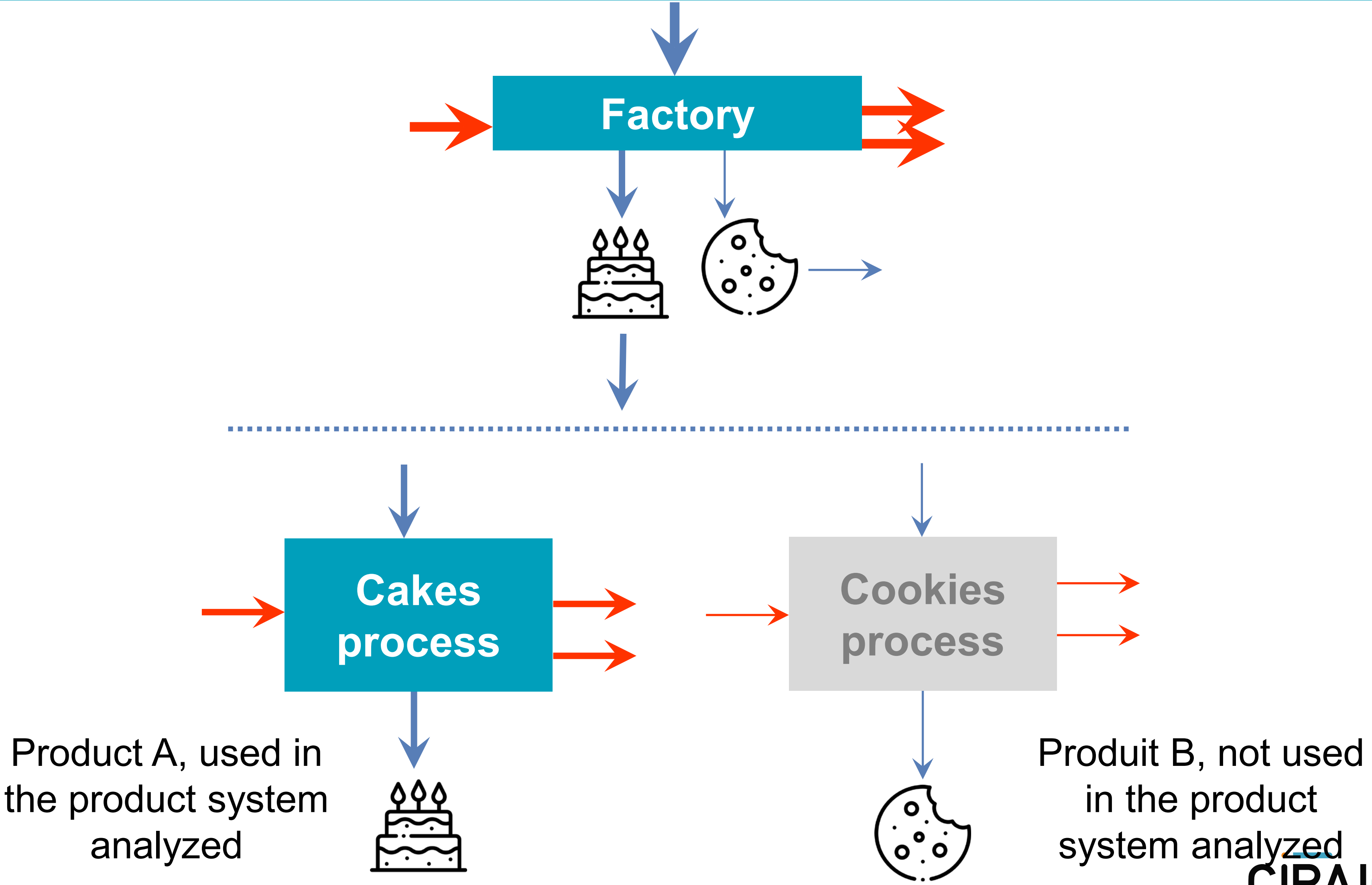
<u>Note</u>: only applicable if the process isn't actually multifunctional : no technological linkage between coproducts (combined production)

ISO 14044 Procedure– Step 1a: Subdivision

- Example: LCA of cakes.

We have data for all inputs and outputs of a factory producing two products: cakes and cookies.

The data collection could be refined to distinguish the processes in the factory that are used for the cake and those used for the cookies.



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How to solve multifunctionality in LCA?

1. Subdivision

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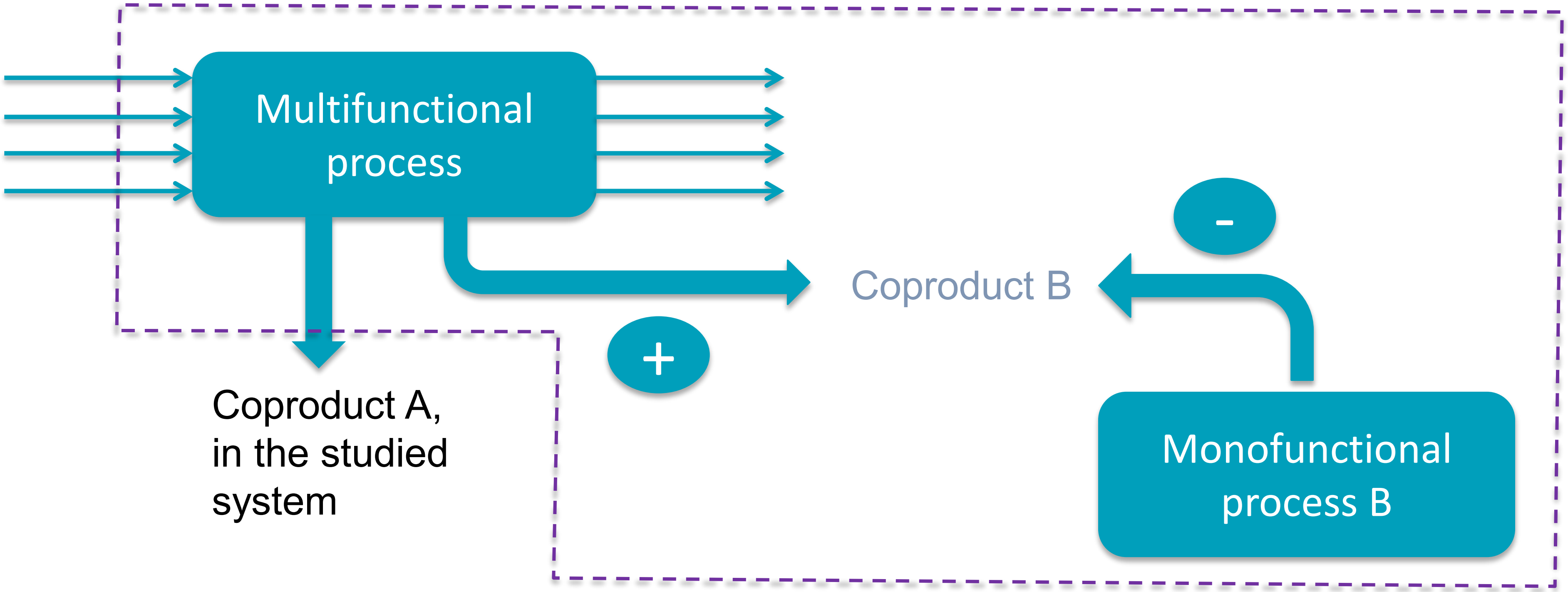
ISO 14044 Procedure– Step 1b: Expanding the system boundary



Step 1.2: Expand the system boundary

Note: Only applicable if there is a process producing a functionally equivalent product to product B

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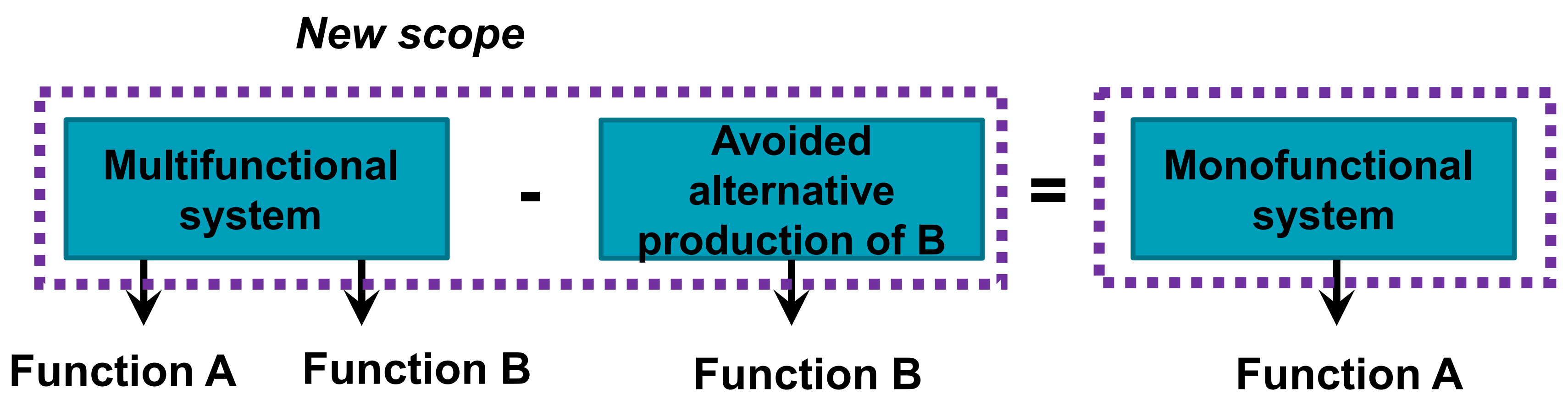
ISO 14044 Procedure– Step 1b: Expanding the system boundary

- In this approach, the product system is expanded to include avoided unit processes
    - LCA on function A, product system A and B
    - We take into account the avoided (negative) alternative way to produce B
      → substitution, displacement, avoidance
    - We consider then that the expanded system is equivalent to a product system that doesn't have function B as an output



ISO 14044 Procedure– Step 1b: Expanding the system boundary

To use system expansion:

1) We need to be able to identify a **competing primary producer** of the co-product that doesn't interest us
   - **Could be especially challenging for prospective modeling, when alternative way to produce do not exist yet**
2) We should pay attention to substitutability ratio which is not always 1:1
   - **Accounting for the efficiency of the co-product and its alternative to provide the same function**

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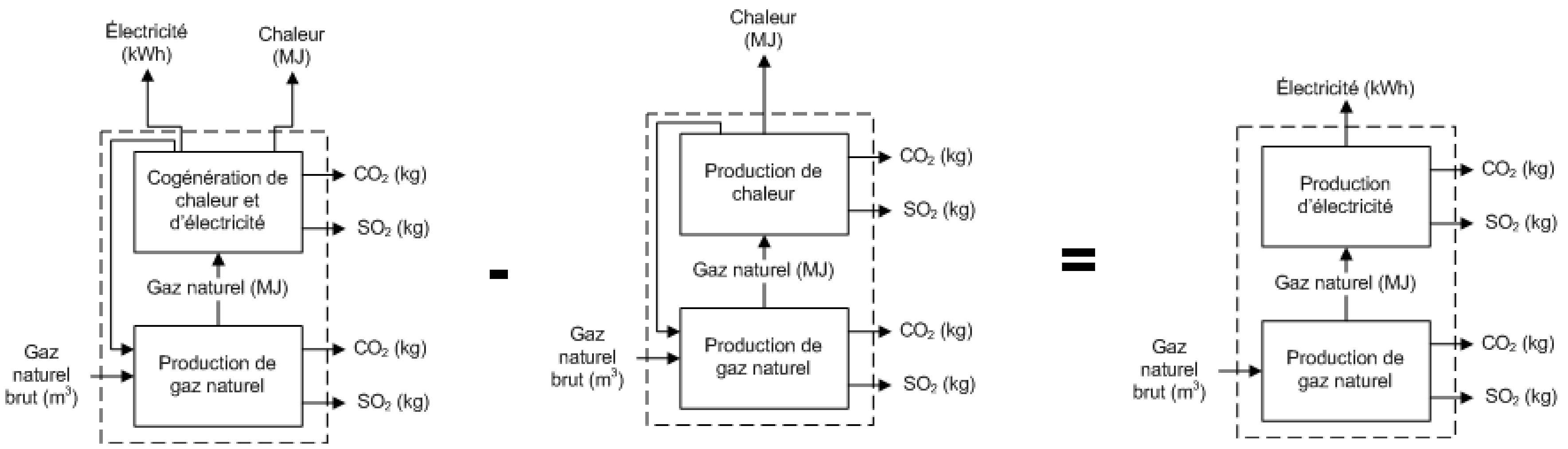
ISO 14044 Procedure– Step 1b: Expanding the system boundary



	p_{cogen}	p_{GN}	$p_{chaleur}$
Electricity (kWh)	1	-2,5	0
Natural gas (MJ)	-10,5	1000	-1.05
Heat (MJ)	1,8	0	1
Raw natural gas (m^3)	0	-25	0
CO_2 (kg)	0,5	10	0,06
SO_2 (kg)	0.25	0.01	6e-7

A→square!

B

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How to solve multifunctionality in LCA?

1. Subdivision

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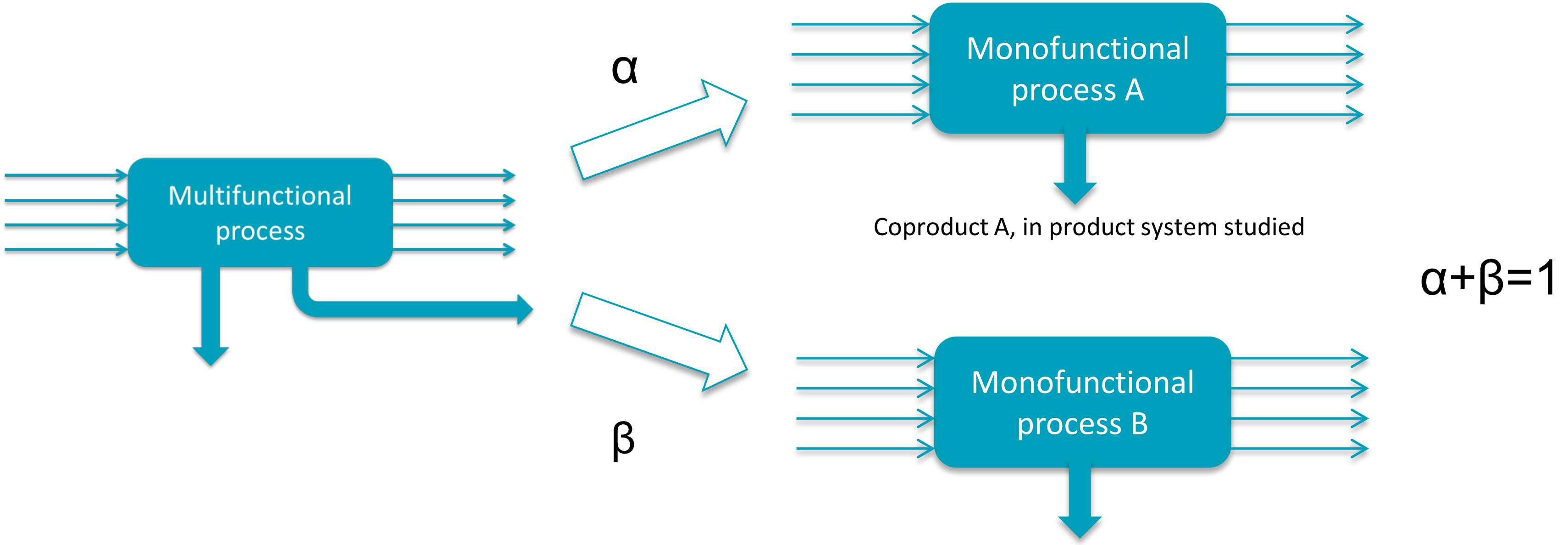
ISO 14044 Procedure – Step 3: Other relationship



Step 3: Attribute according to other mutual relationship (economic value, mass, surface, exergy, etc.)

Note: Useful for joint production. Results in process where conservation laws <u>only works for the chosen relationship</u>.

ISO 14044 Procedure – Step 3: Other relationship

→ Applies to **joint productions**

- The inputs and outputs are divided between the different products
  - **According to a physical property (e.g. mass, energy, surface)**
  - **According to economic value of the co-products**
  - **According to another valuable relationship**

- **Causality principle : the factors used to allocate a flow to a product should reflect the degree of responsability of the product for generating that flow**

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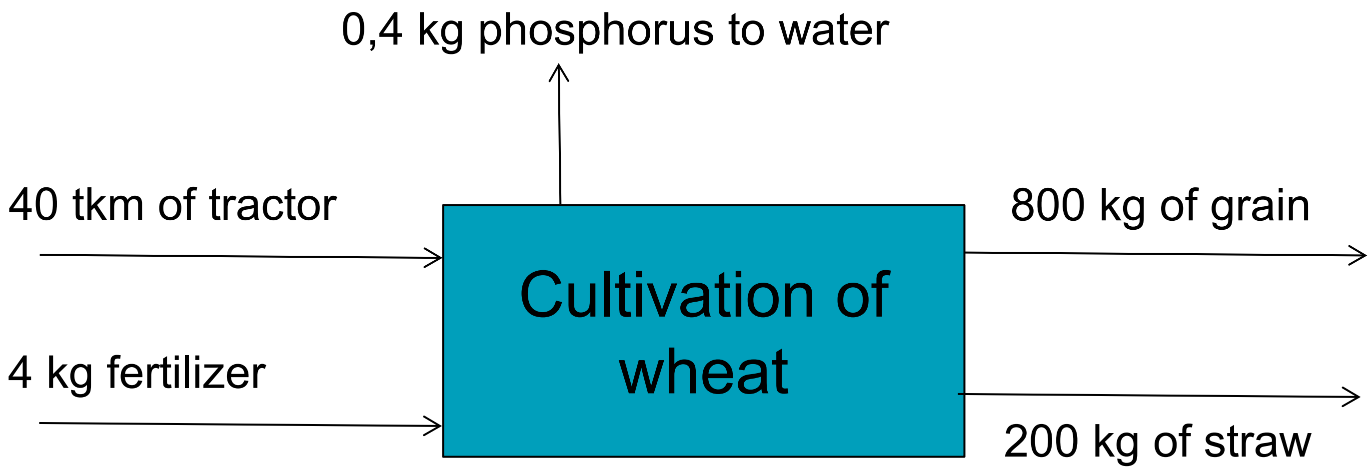
ISO 14044 Procedure – Step 3: Other relationship

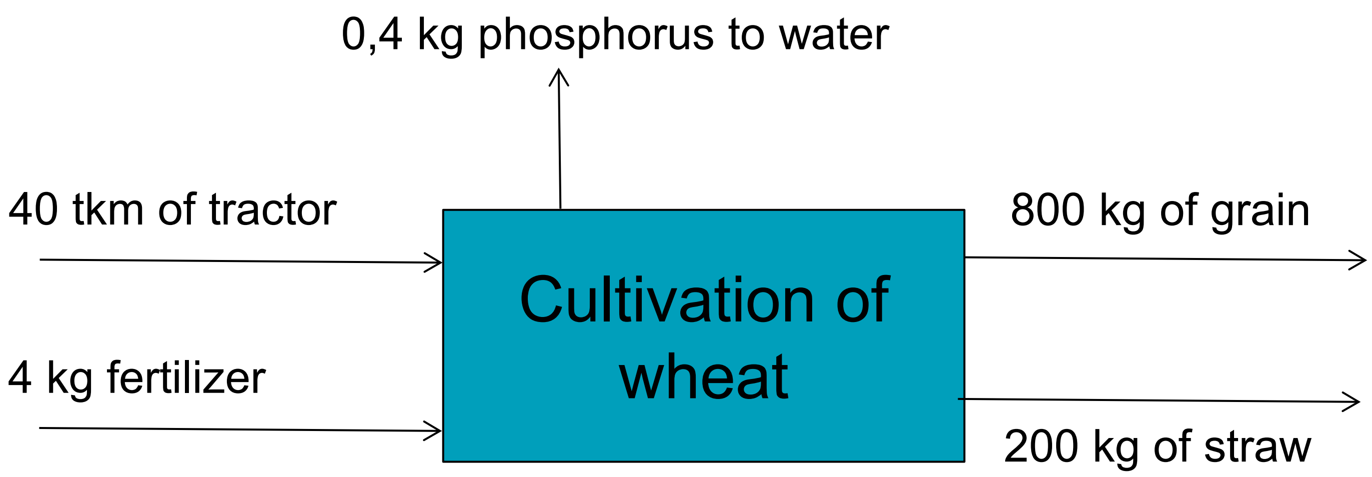
- Allocation example



- Choice of allocation basis: mass
- The two products are measured by their mass

ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: mass



- Total mass produced: 800 + 200 = 1000 kg
- Allocation factor for grain = 800/1000 = 80%
- Allocation factor for straw = 200/1000 = 20%

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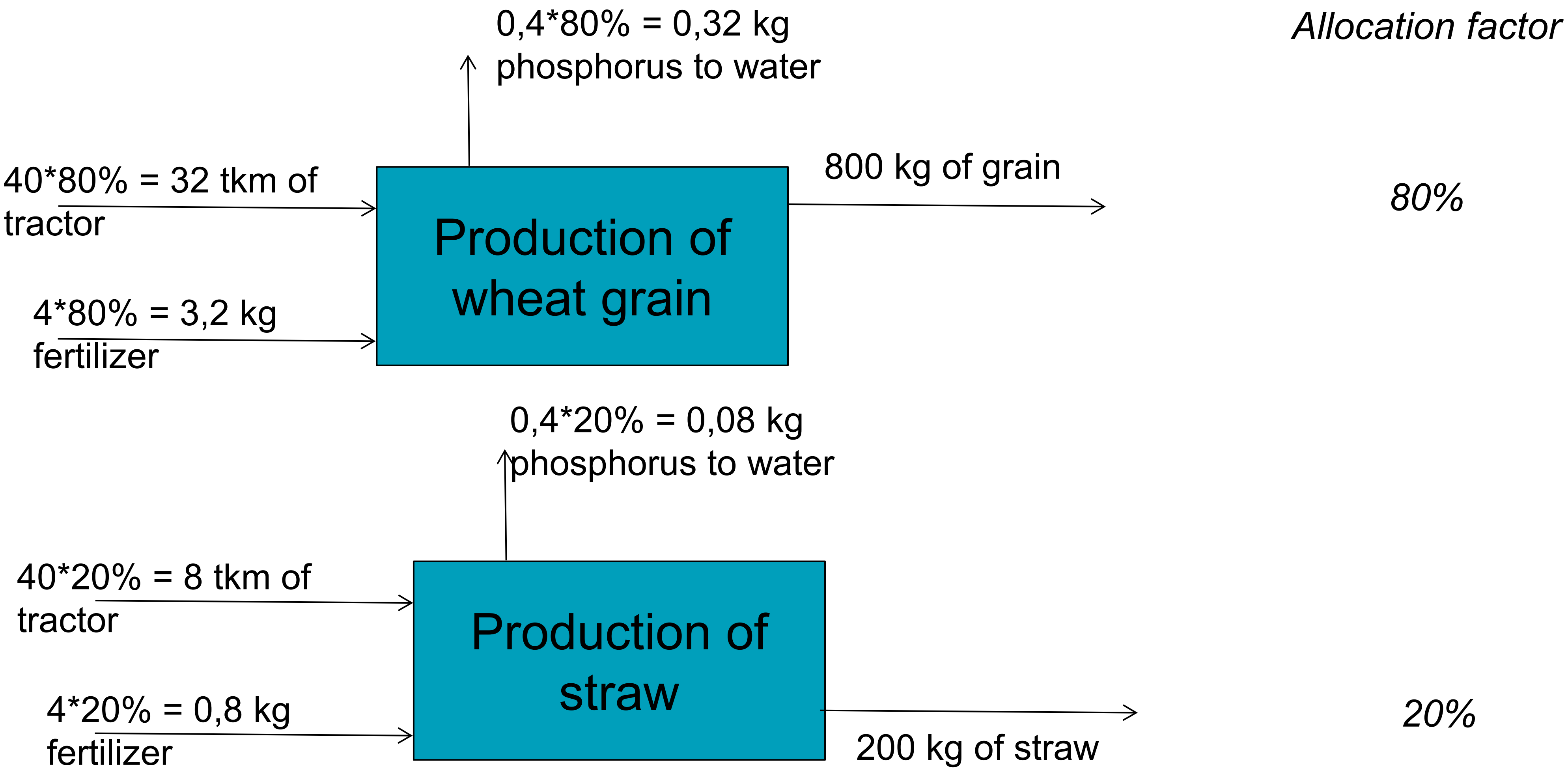
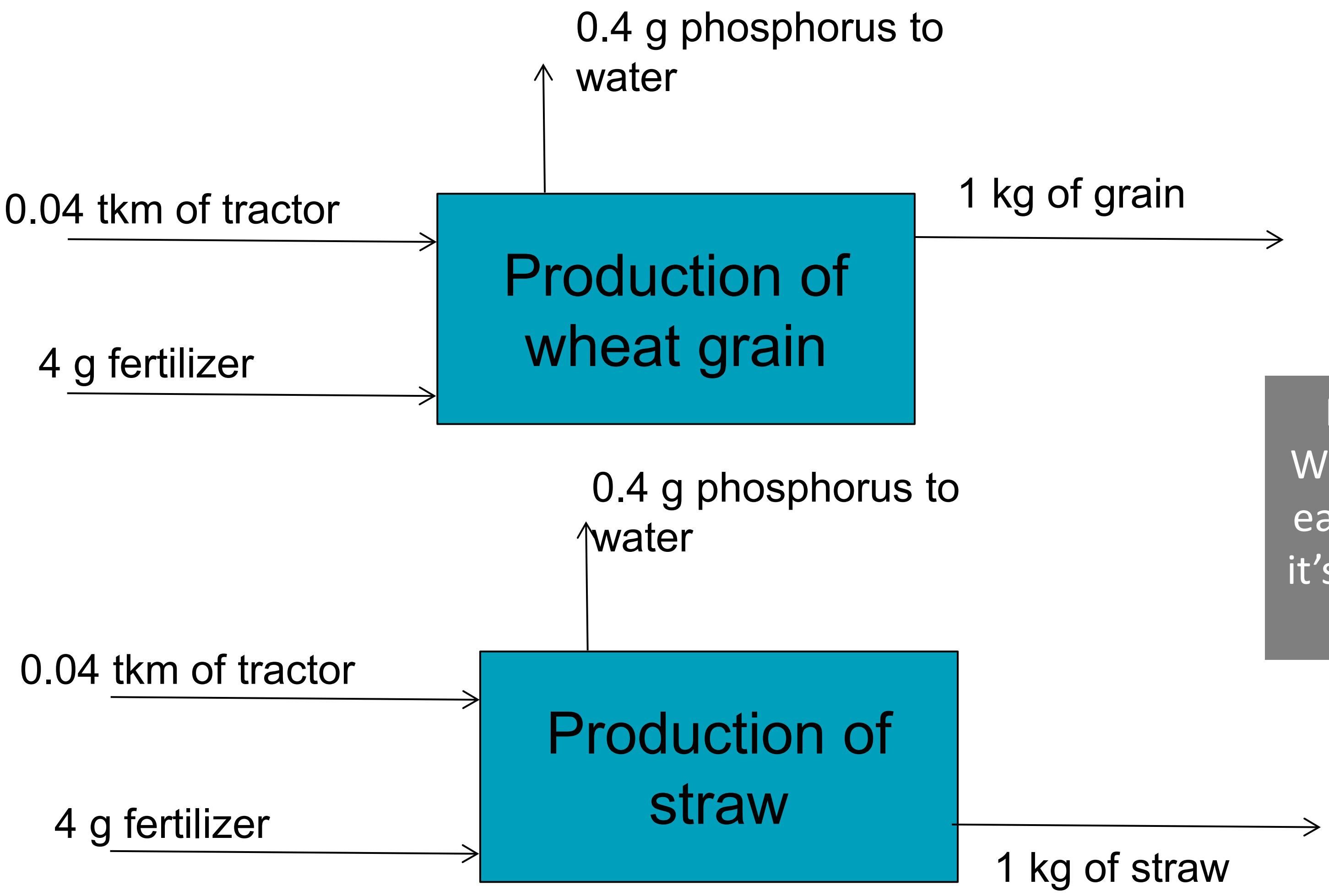
ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: mass



ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: mass



Allocation factor

80%

20%

Meaning of mass allocation
We allocate the same burden to each kg of outputs (no matter if it's a kg of grain or a kg of straw)

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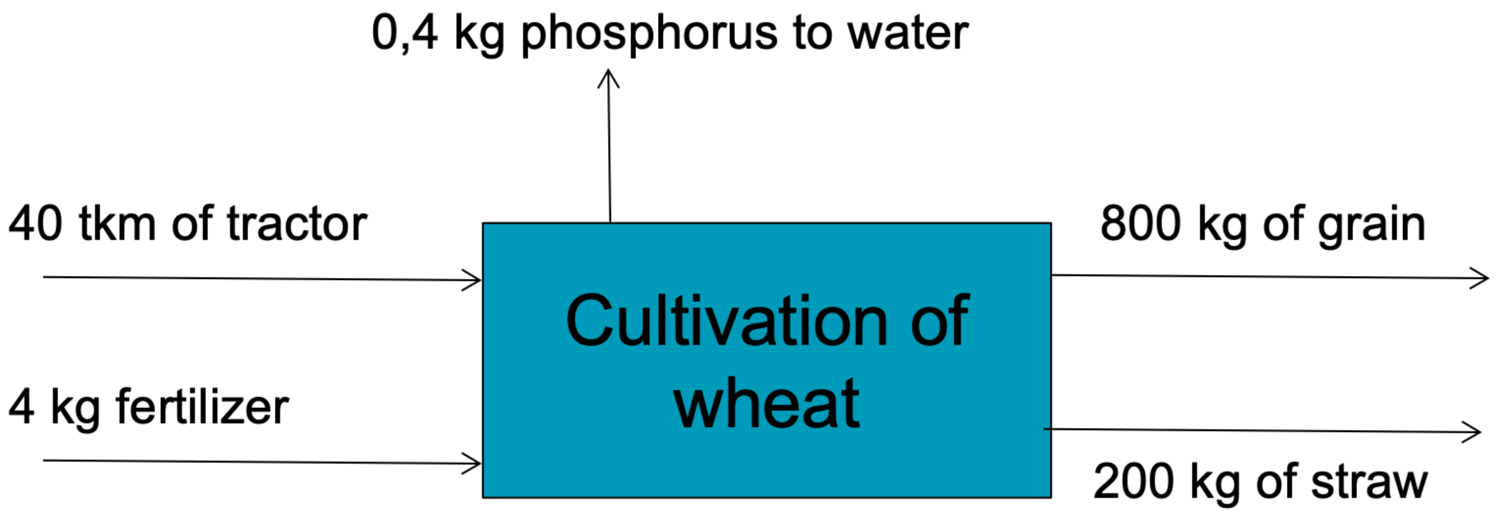
ISO 14044 Procedure – Step 3: Other relationship

- Example of economic allocation
  - **Let's take the same process, but let's use an economic allocation**
  - **Let's suppose the following prices:**
    - Wheat grains: 0,25$/kg
    - Straw: 0,1$/kg



ISO 14044 Procedure – Step 3: Other relationship

- Example of economic allocation
  - **Let's take the same process, but let's use an economic allocation**
  - **Let's suppose the following prices:**
    - Wheat grains: 0,25$/kg
    - Straw: 0,1$/kg

- Total revenue: 800 kg * 0,25 $/kg + 200 kg * 0,1 $/kg = 220$
- Allocation factor for grain = 200/220 = 91%
- Allocation factor for straw = 20/220 = 9%

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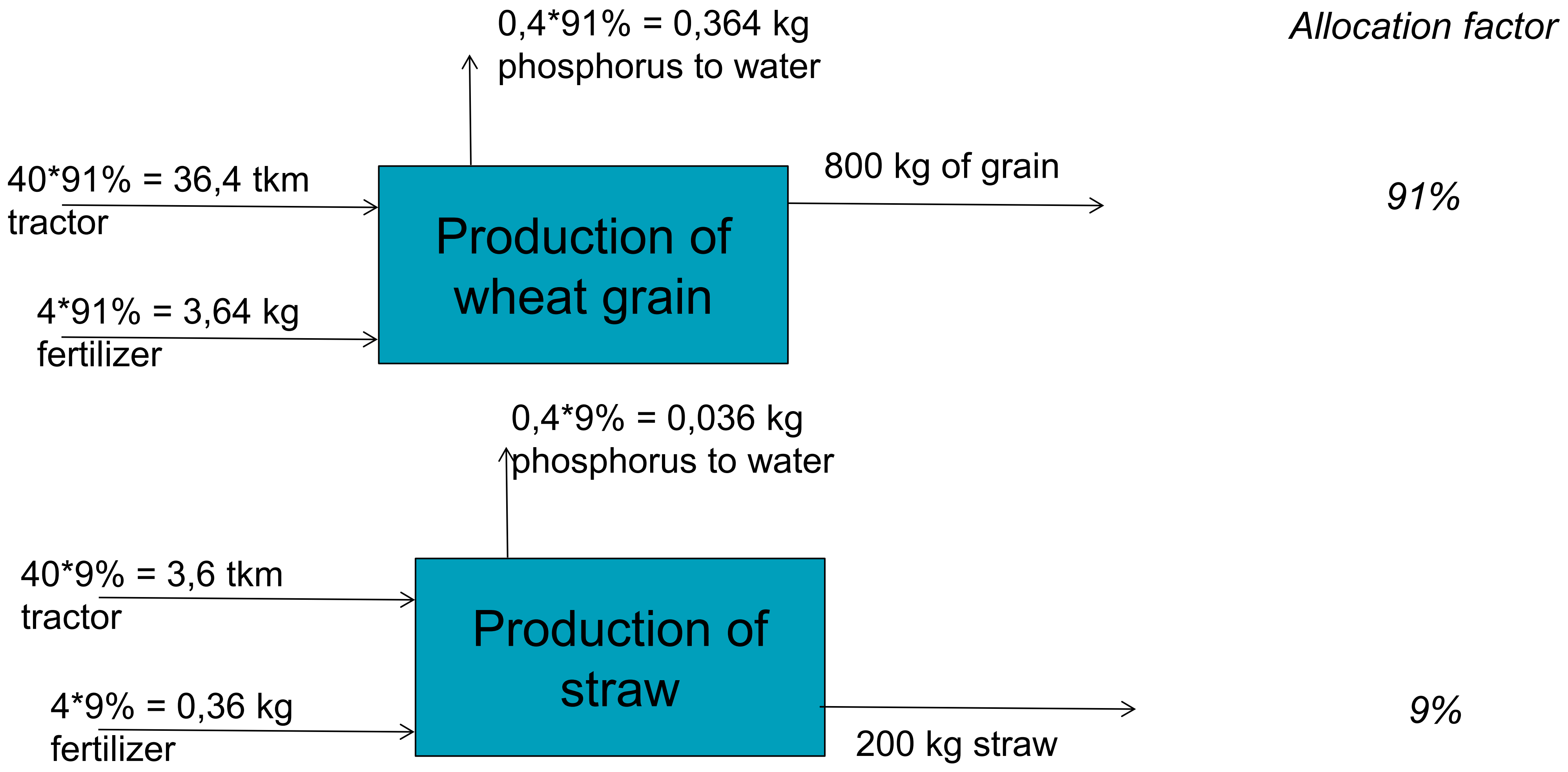
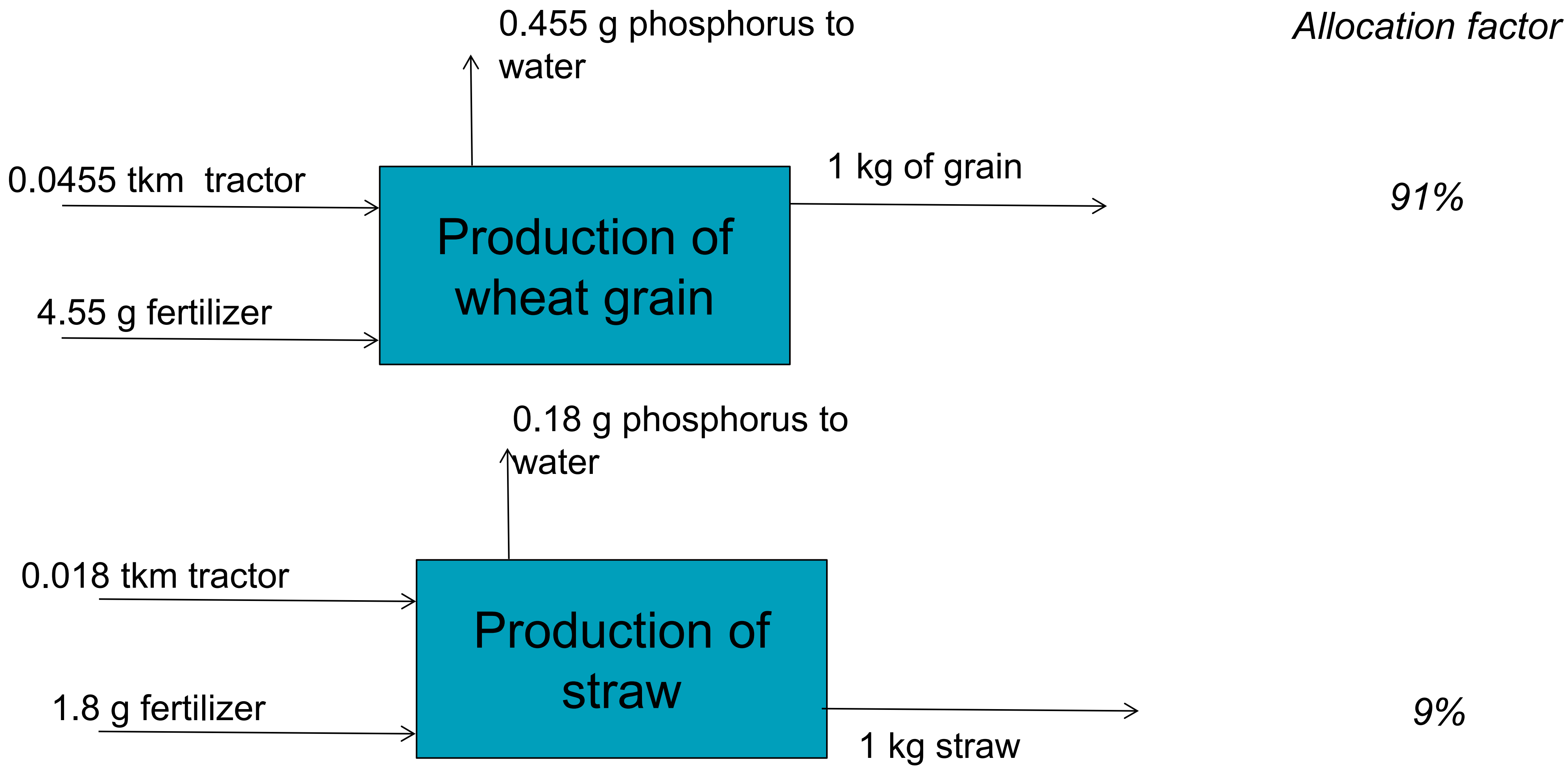
ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: economic



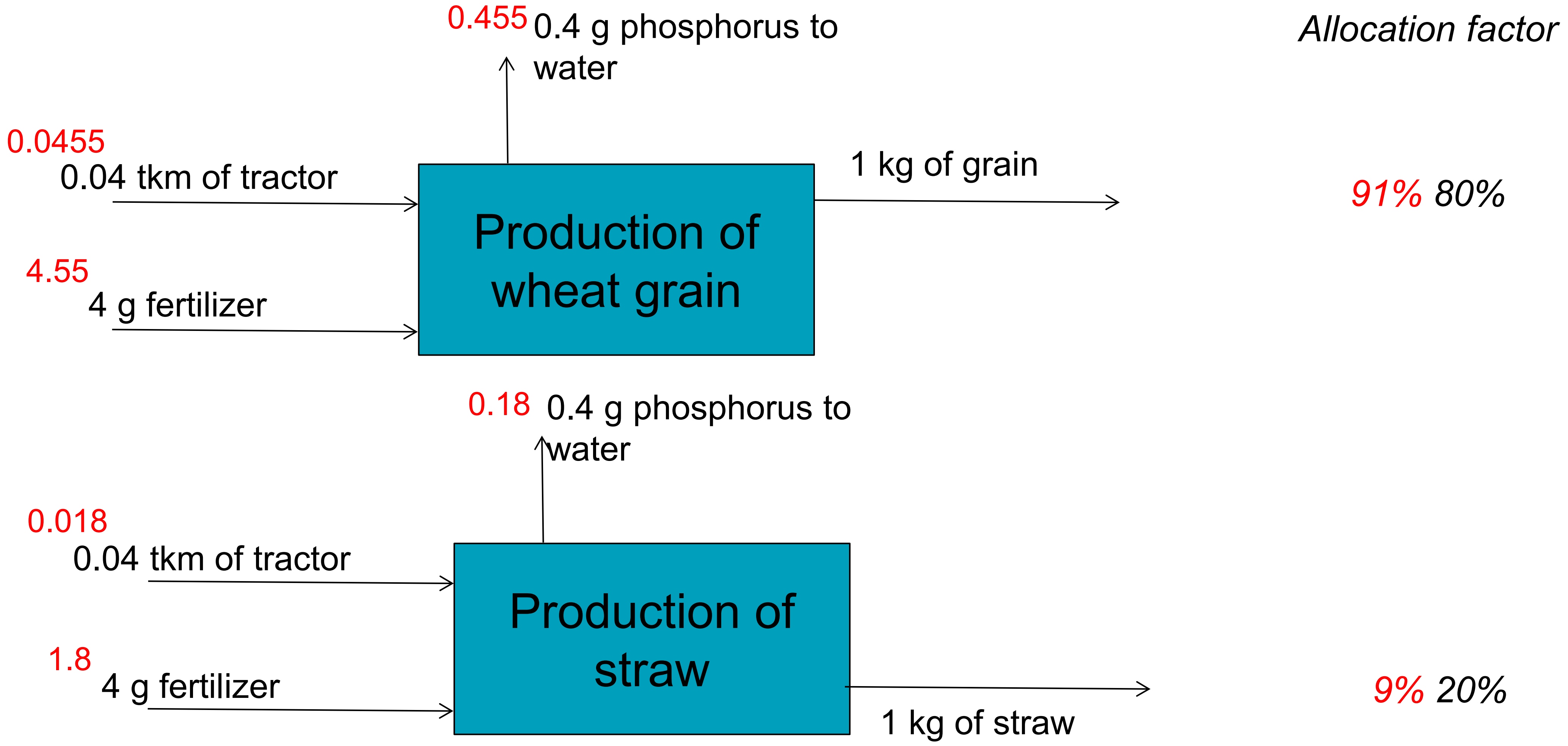
ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: economic



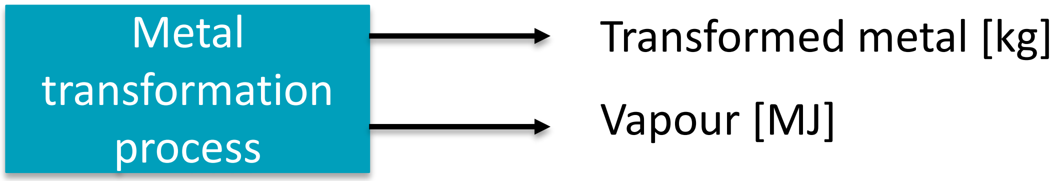
ISO 14044 Procedure – Step 3: Other relationship

- Allocation example: mass vs economic



ISO 14044 Procedure – Step 3: Other relationship

- Another example of economic allocation



  - **A factory transforms metal with a process using heat. A heat recovery machine produces steam that is sold to a factory nearby.**
  - **Inconsistent data properties → economic allocation**
  - **The factory sells metal at a price of 45 $/kg, and steam at 5 $/MJ**
  - **Allocation factor for metal: 45 / (45 + 5) = 90% ?**
    - NO!!!!!! We cannot add the prices, but we could add the revenues.
  - **Over one year, the factory produces 300 tonnes of metal and 800 GJ of steam**

ISO 14044 Procedure – Step 3: Other relationship

- Example of economic allocation
  - **The factory sells metal at a price of 45 $/kg, and steam at 5 $/MJ**
  - **Over one year, the factory produces 300 tonnes of metal and 800 GJ of steam**

Product	Quantity	Price	Revenues	Allocation factor
Metal	300E3 kg	45$/kg	13500 k$	77,1%
Steam	800E3 MJ	5$/MJ	4000 k$	22,9%

ISO 14044 Procedure – Step 3: Other relationship - examples

Crude oil

Gasoline [L]

Natural gas [m3]

Chemical products [kg]

Common property?

Machinery

Explosives

Combustibles

Gravel [tonnes]

Diamonds [g]

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ISO 14044 Procedure – Step 3: Other relationship - examples

Crude oil

Gasoline [L]

Natural gas [m3]

Chemical products [kg]

→ Volumic allocation would make no sense!
→ Economic value? Calorific value?

Machinery

Explosives

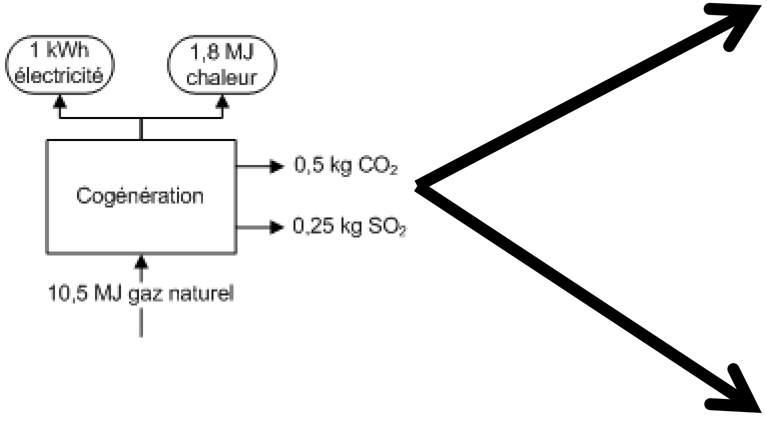
Combustibles

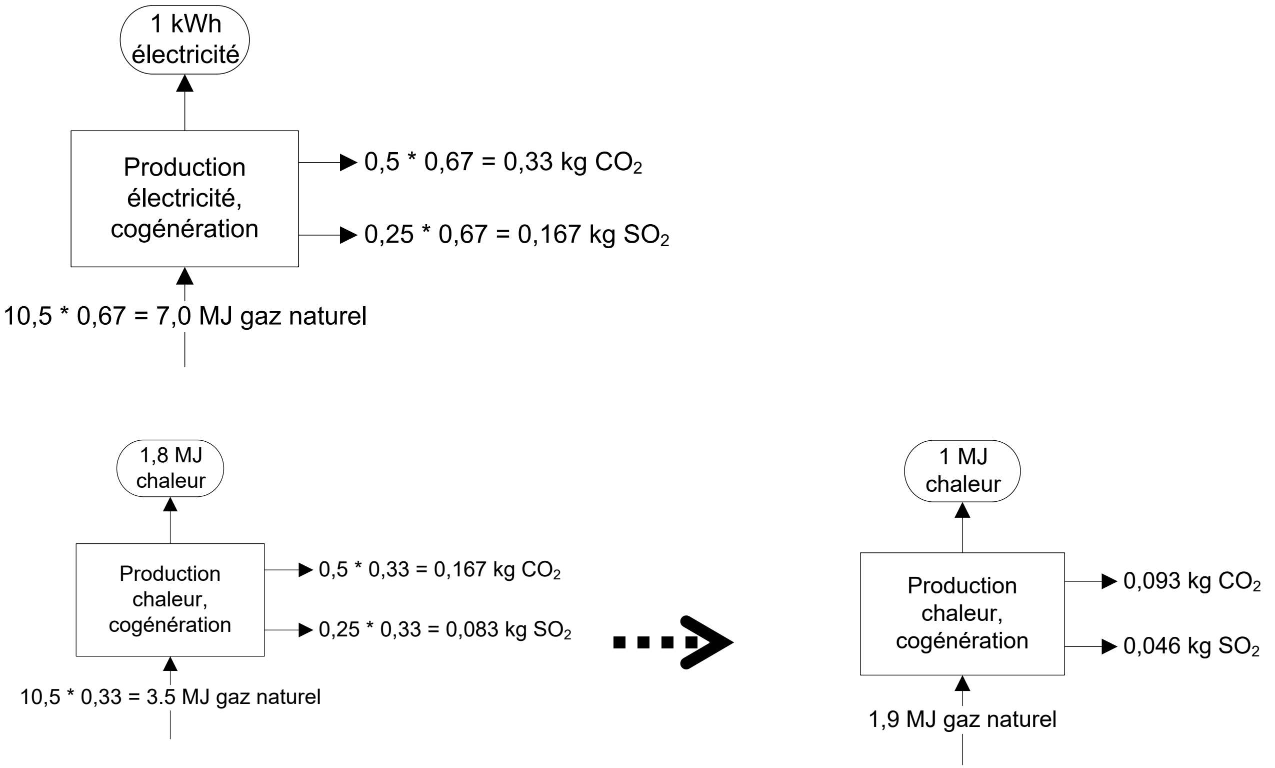
Gravel [tonnes]

Diamonds [g]

→ Economic allocation: Diamond exploitation is the existing reason of the process (high added value)!

ISO 14044 Procedure – Step 3: Other relationship





- Two co-products
- Coherent units, with conversion (MJ, kWh)
- Are they comparable? Let's say yes...
- Basis of allocation chosen: Energy. We suppose that heat and electricity are both useful to do work (which is not necessarily true…→ exergy would be a better metric)
- Calculating the allocation factors:
  - **Total energy: 1 kWh * (3,6 MJ/kWh) + 1,8 MJ = 5,4 MJ**
  - **Allocation factor electricity: 3,6/5,4 = 0.67**
  - **Allocation factor heat: 1,8/5,4 = 0.33**
- Apply the factors
- Re-normalize, if needed

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Multifunctional processes - Allocation

	p_{cogen}	p_{GN}	
Electricity (kWh)	1	-2,5	A
Natural gas (MJ)	-10,5	1000	
Heat (MJ)	1,8	0	
Raw natural gas (m^3)	0	-25	B
CO_2 (kg)	0,5	10	
SO_2 (kg)	0,25	0,01	

	p_{elect}	p_{GN}	$p_{chaleur}$	
Electricity (kWh)	1	-2,5	0	A
Natural gas (MJ)	-7	1000	-1,9	Square!
Heat (MJ)	0	0	1	
Raw natural gas (m^3)	0	-25	0	B
CO_2 (kg)	0,33	10	0,093	
SO_2 (kg)	0,167	0,01	0,046	

How to solve multifunctionality in LCA?

1. Subdivision

2. System expansion

3. Allocation based on underlying physical relationship

4. Allocation based on other relations

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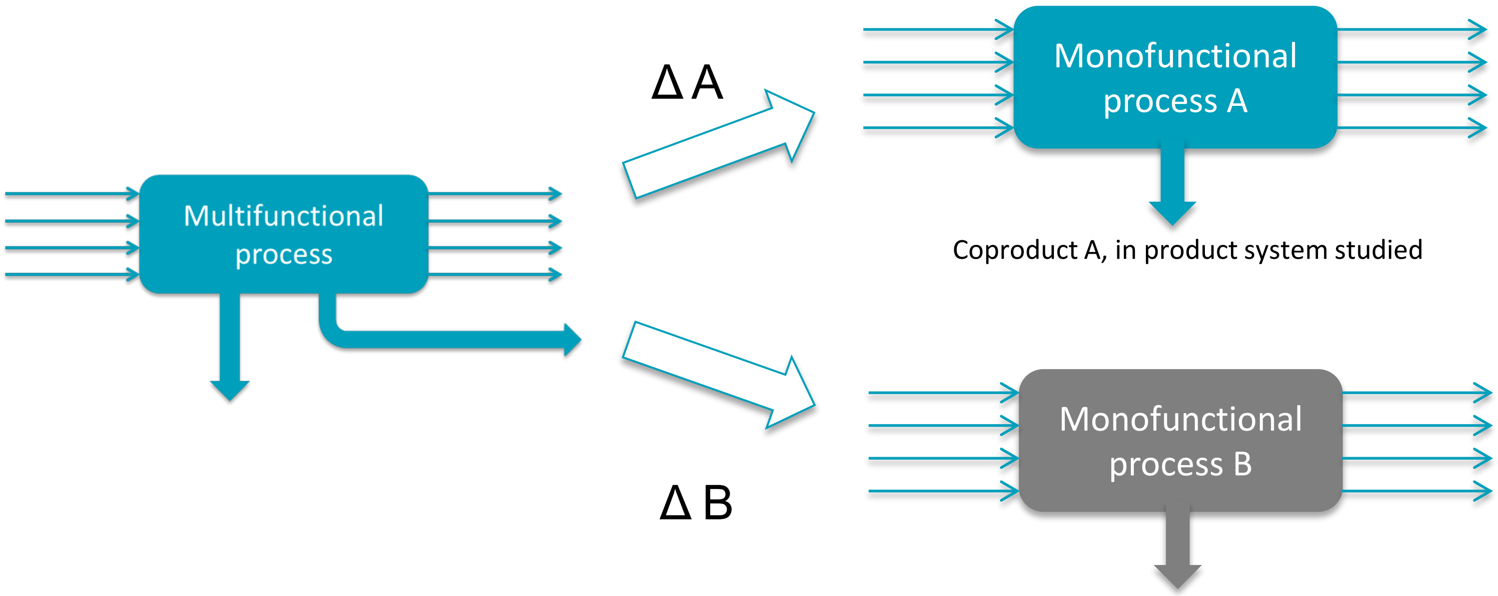
ISO 14044 Procedure – Step 2: underlying physical relationships



Step 2: Allocate between products in a way that reflects underlying physical relationships existing between them

<u>Note</u>: only applicable if we can vary the co-products independently (combined production)

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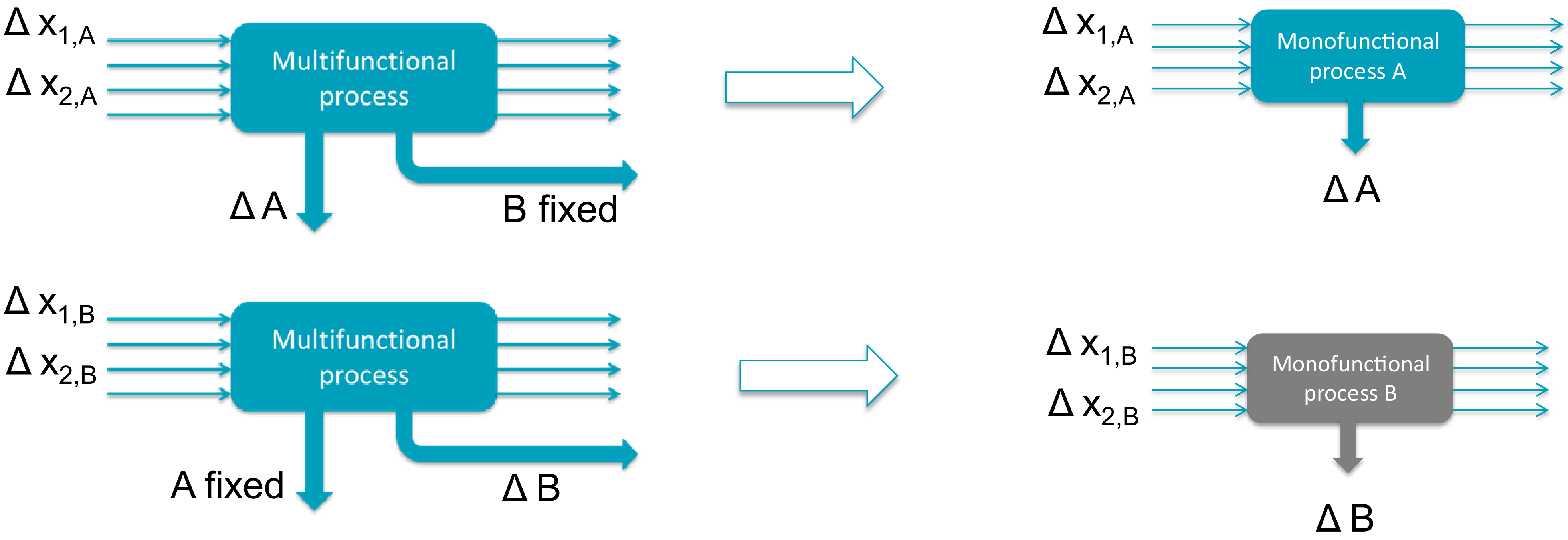
ISO 14044 Procedure – Step 2: underlying physical relationships



This method allows us to determine how the inputs and outputs are affected by an increase in production of one of the co-products → This information is used to estimate the inputs and outputs associated to one co-product only

<u>Note</u>: only applicable if we can vary the co-products independently (combined production)

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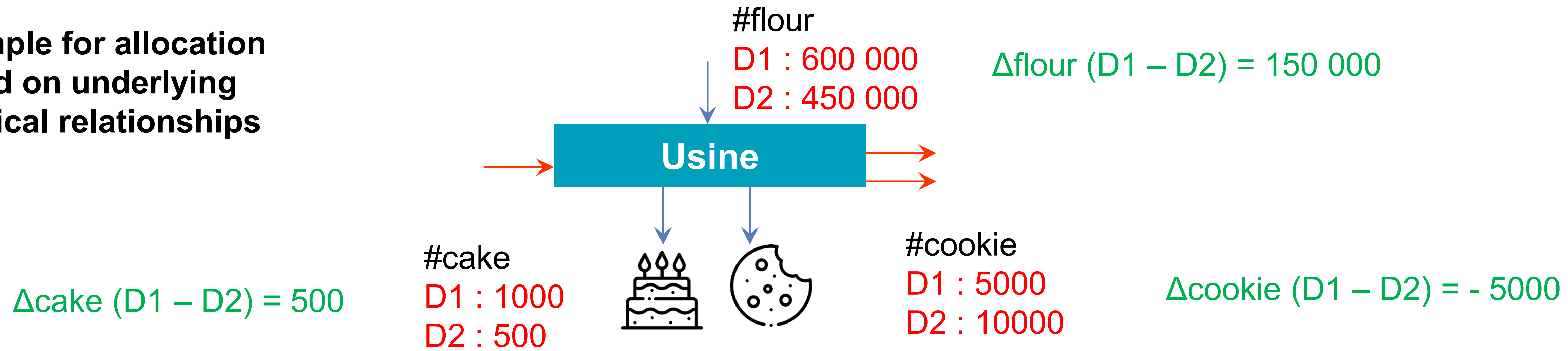
ISO 14044 Procedure – Step 2: underlying physical relationships

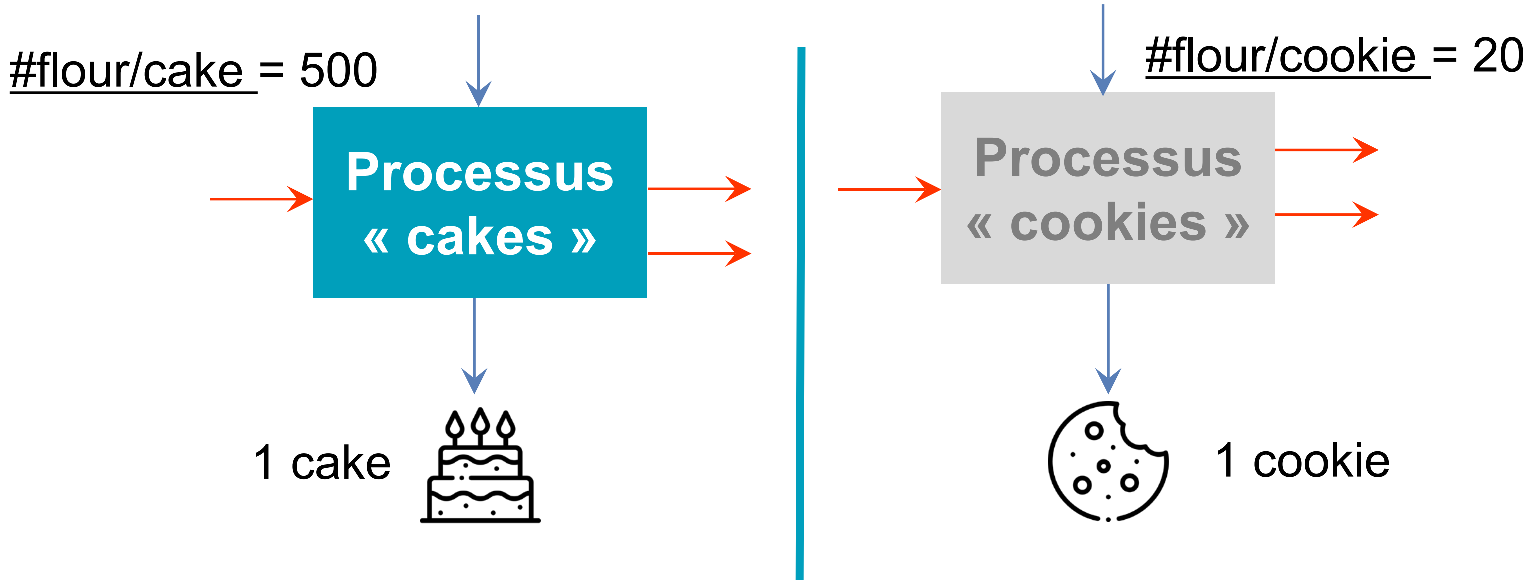
- Examples of **<u>combined productions</u>** where the quantity of co-products can vary independently
  - **A chemical reaction where the proportion of products can be controlled according to the proportions of reactants in input is an example of combined production with independently varying amounts of co-product. In this case, the quantities of inputs and outputs allocated to each reaction product are based on stoichiometric ratios.**
  - **Another example is the allocation of the amount of fuel needed to transport a product between the product itself and its packaging based on the payload used. Indeed, it is possible to vary the packaging quantity regardless of the product quantity.**
- Coming back to LCA example of the factory producing cakes and cookies:
  - **If it's impossible to simply attribute the different unit processes inside the factory to those producing cakes, we could vary the quantity of cakes produced: this would affect the inputs and outputs of the factory**
  - **In this way, we could determine which inputs are directly attributable to cakes**
- Not to be confused with applying an allocation based on a physical property like mass!

Example for allocation based on underlying physical relationships



Equation system to be solved to find #flour/cake and #flour/cookie

- For D1 (ou D2) : #flour = #cake x #flour/cake + #cookie x #flour/cookie
- For D1-D2 : Δflour = Δcake x #flour/cake + Δcookie x #flour/cookie



How to choose the approach to address multifonctionality?

1. Subdivision

2. System expansion

3. Allocation based on underlying physical relationship

4. Allocation based on other relations

Debate in the LCA community

Validity framework, strenghts and weaknesses of each approach

Approach	Framework of validity of the approach	Potential reasons for non-applicability of the approach	Advantages of the approach	Disadvantages of the approach
Subdivision	• **Combined production** of co-products (non-joined): quantities of co-products vary independently	• Processes are too intertwined to be separated • If detailed information on the different processes are not available	• Represents the real situation in a very detailed manner • Avoid subjective choices	• Data requirement is very high and can be confidential
System expansion / substitution	• **Joint production** of co-products: quantities of co-products vary in a dependent manner	• No avoided product can be identified • No access to data on substitute pathway	• Reflects the physical and economic implications of co-product generation • Conservation of mass, energy or other content balances	• Need for additional LCI data • Substitution pathways can be difficult to identify and model • Choice of substitution pathways can greatly influence results • The degree of substitutability between a product and its substitute should be taken into account
Allocation based on underlying physical relationship	• **Combined production** of co-products (non-joined): quantities of co-products vary independently	• No access to data to determine the physical causality	• Less subjective because based on natural science	• Can misrepresent the reasons for operating a process, especially when co-products have very different economic values • Often confused with an allocation based on a common physical property between co-products, such as mass or energy content
Economic allocation	• **Joint production** of co-products: quantities of co-products vary in a dependent manner • If a co-product avoids the production of another product	• No access price data to calculate the allocation factor, especially if co-products at the point of allocation do not yet have a market value.	• Reflects the reasons for operating a process • Differentiates similar products with different qualities	• Prices are highly variable over time (volatility), between regions, between different market players and according to market conditions (monopolies, regulations, subsidies). Economic allocation factors can therefore be unstable. • Price choice can greatly influence results (value choice) • Price data for intermediate products or for prospective scenarios can be difficult to estimate. • Non-conservation of mass balances
Mass allocation		• If not all co-products from the same multifunctional process have a directly defined mass. E.g. heat co-production	• Often easy to apply • Conservation of mass balances	• May misrepresent the reasons for operating a process, especially when co-products have very different economic values
Energetic allocation			• Allows allocation of products with no directly defined mass. e.g. heat in the form of steam Conservation of energy balances	• May misrepresent the reasons for operating a process when not all co-products are used for their energy content • Non-preservation of mass balances • Does not reflect the useful energy of co-products if exergy is not the energy property used

Patouillard, L., Maxime, D., Menard, J.-F., De Wachter, H., Greffe, T., & Bolay, A.-F. (2022). Analyse du cycle de vie de la biomasse énergie : état de l'art, enjeux méthodologiques et recommandations. SCORELCA.

How to choose the approach to address multifunctionality?

According to the
UNEP Life Cycle Initiative (2016) …

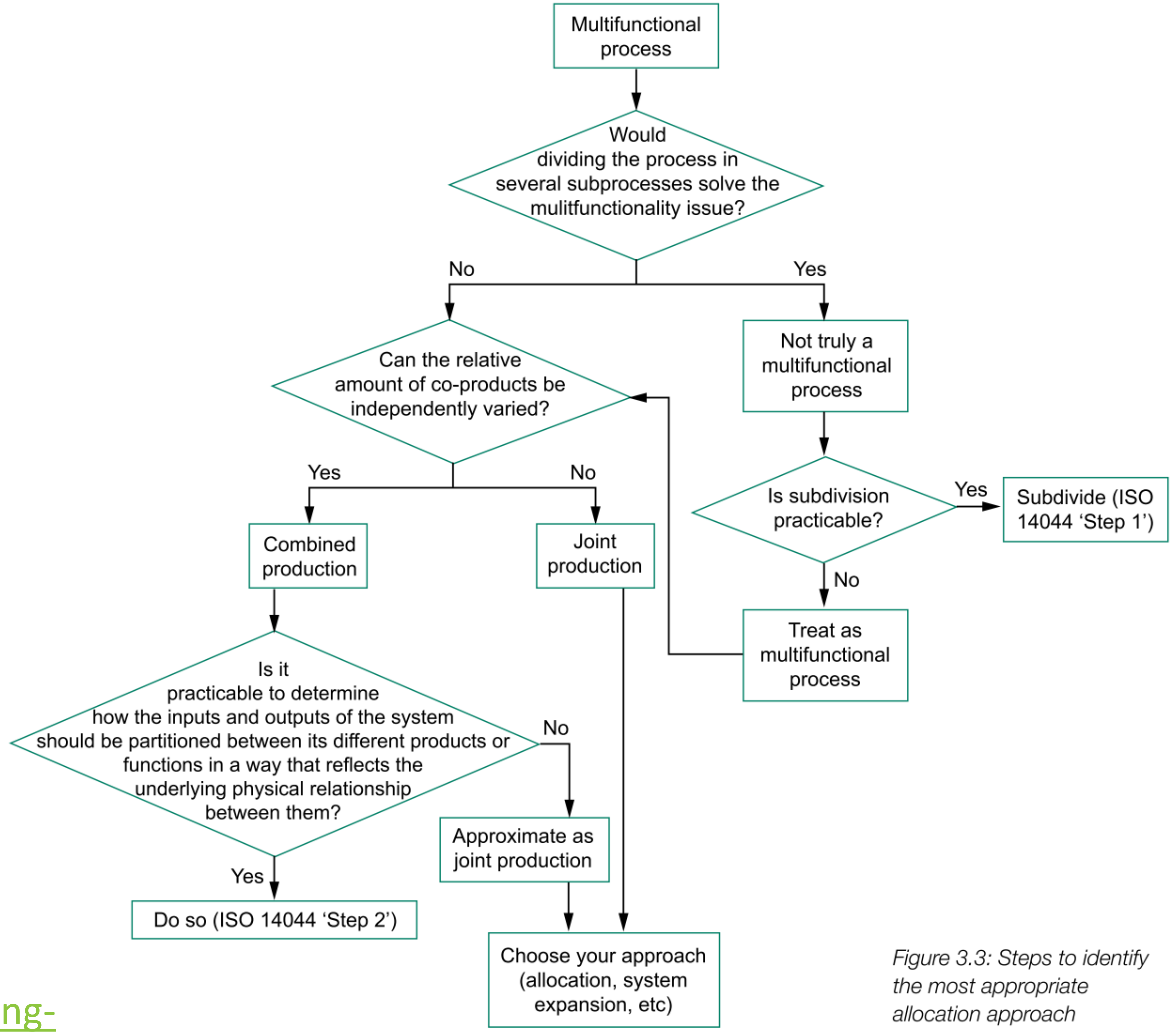


Figure 3.3: Steps to identify the most appropriate allocation approach

Life Cycle Initiative. (2016)
Steps to identify the most appropriate allocation approach.
Retrieved from: https://www.lifecycleinitiative.org/training-resources/global-guidance-principles-ggp-on-life-cycle-assessment-data-and-databases/

ISO 14044 Procedure - multifunctionality

- « Attributing impacts » to a co-product is entirely imaginary. In reality, the co-products will always be manufactured together. For this reason, allocation is an arbitrary operation subject to debate.

The choice of allocation approach can change the results and the conclusion of a study!!!

- Like anytime, there are assumptions in LCA, transparency is necessary.
- When in doubt, or if controversy arises on the best method to use, perform a scenario/sensitivity analysis

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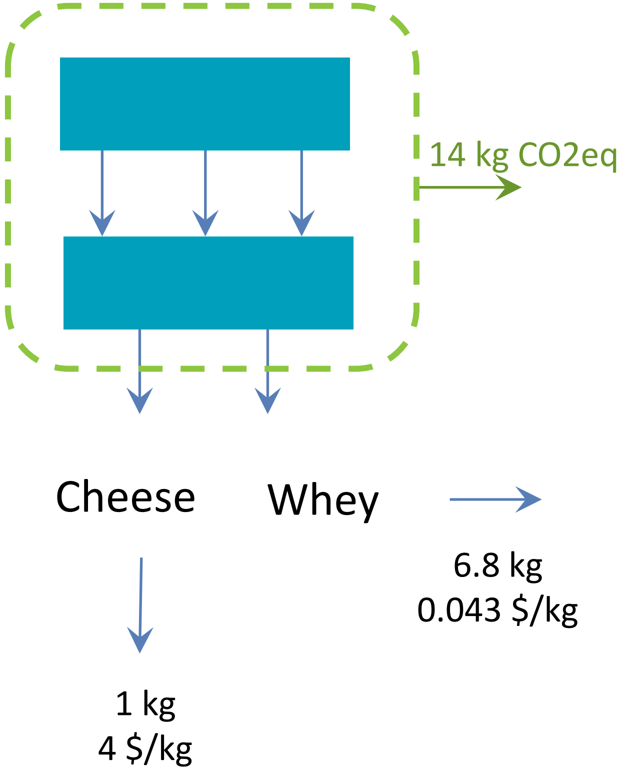
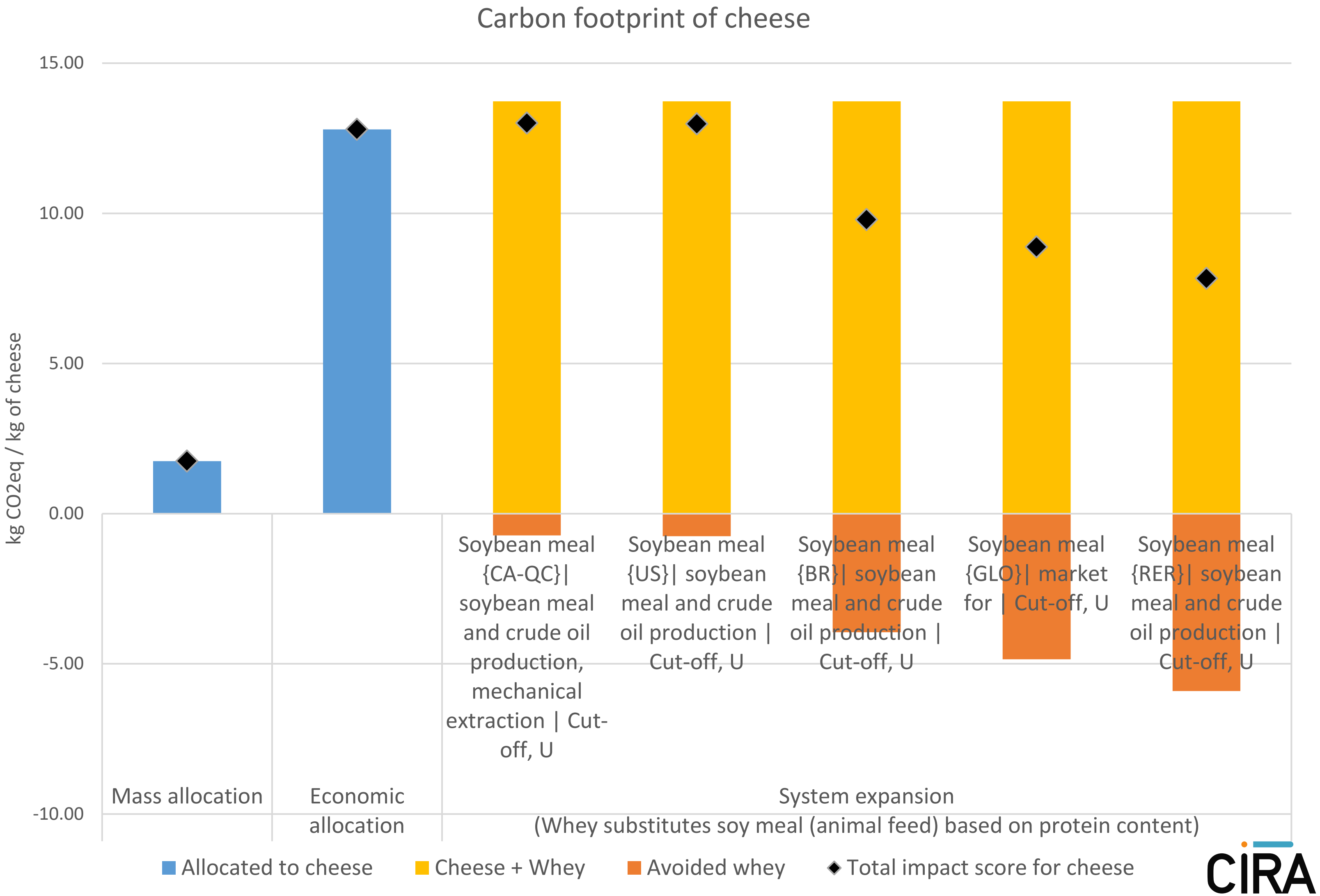
Influence of the choice of the approach to address multifunctionality





MULTIFUNCTIONALITY AND RECYCLING

Open-loop recycling

Open-loop recycling has two functions, each associated to its respective product system

Elimination of waste from product system A

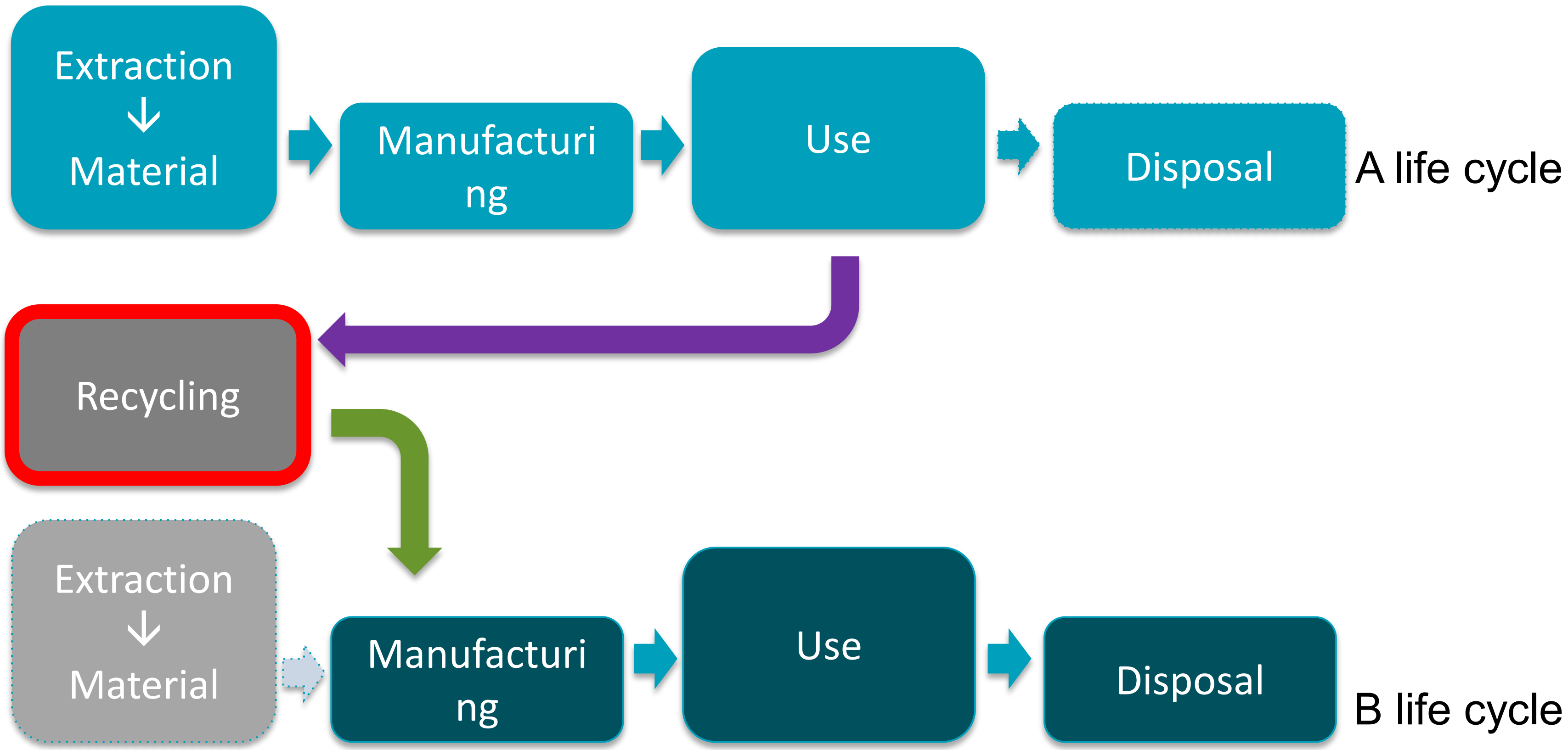
Recycling

Recycled material used in product system B

For a study we can generate waste that will be recycled AND/OR use recycled material

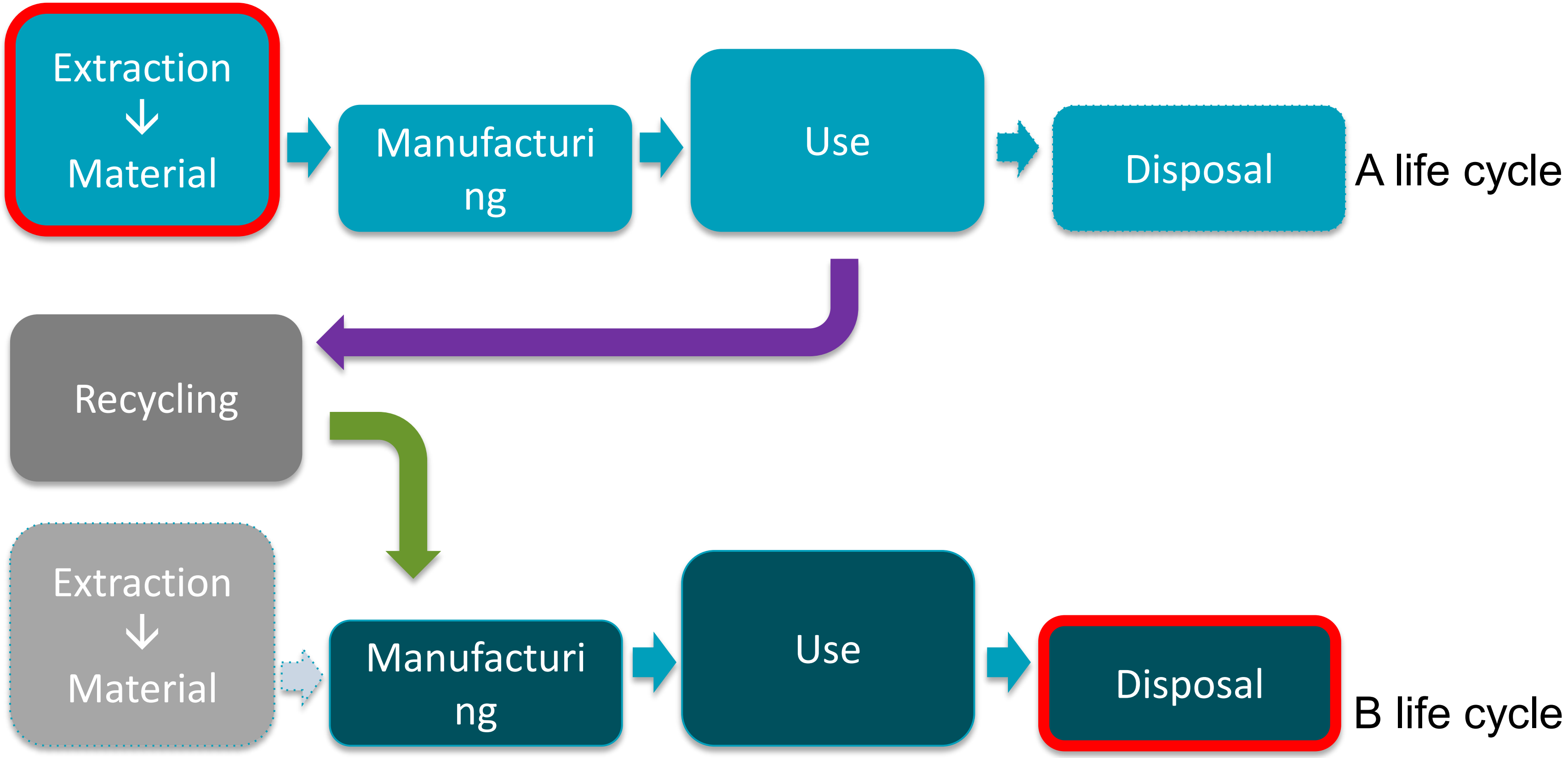
Open-loop recycling

Who is responsible for the impacts of recycling?



Open-loop recycling

Who is responsible for the impacts of the production of initial virgin material?
Who is responsible for the impacts of final disposal?



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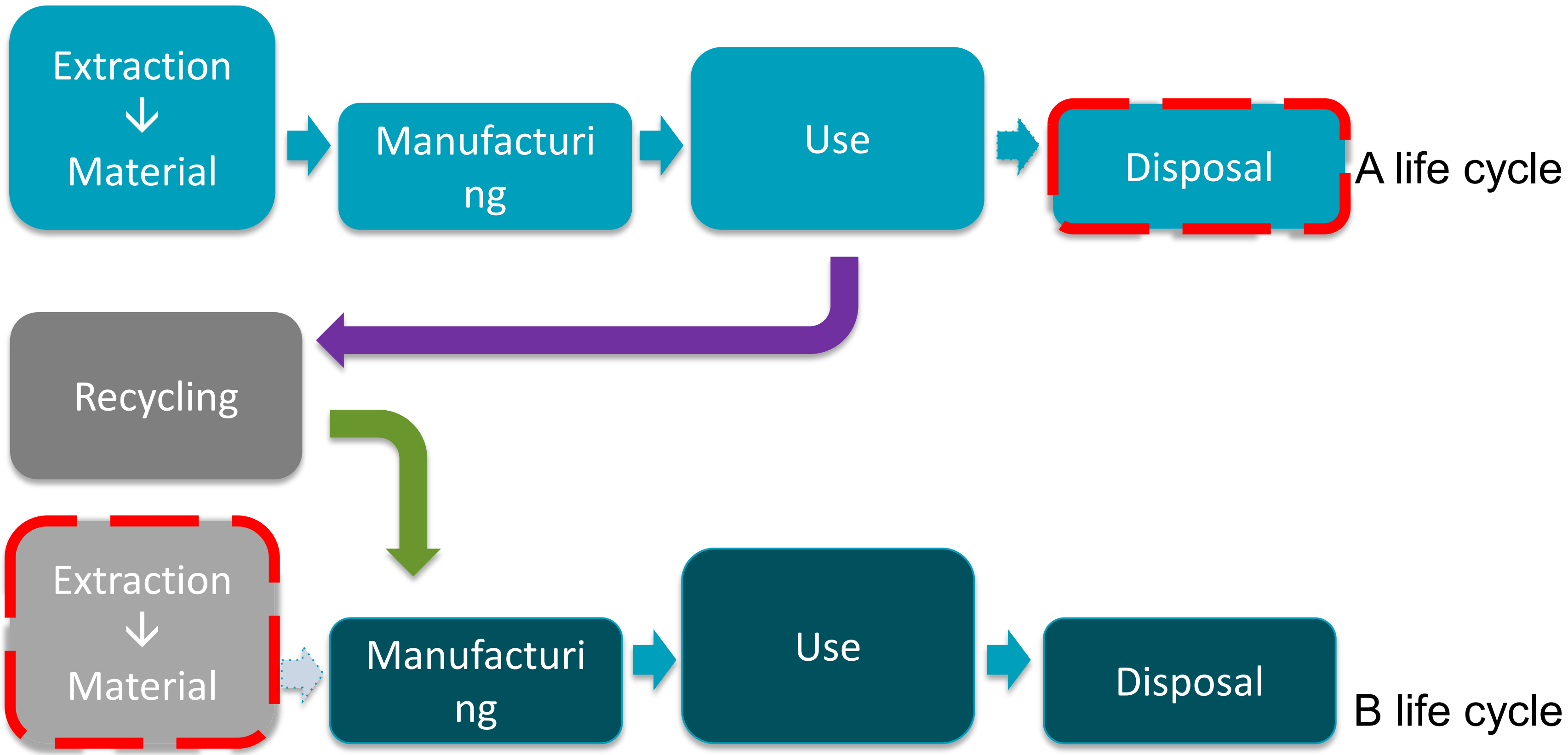
Open-loop recycling

Who takes credits for the avoided impacts of disposal?
Who take credits for the avoided impacts of the production of virgin raw material?



Most common approaches

- **Recycled content method**
- **End of life recycling method**

- There are more:
  - **Circular Footprint Formula (CFF)**
    https://ec.europa.eu/environment/eussd/pdf/Webinar%20CFF%20Circular%20Footprint%20Formula_final-shown_8Oct2019.pdf
  - **Method of number of uses (usually used for paper, but not covered in this course)**
  - **Methods based on the quality of the recycled material**
  - **50-50 method**
  - **…**

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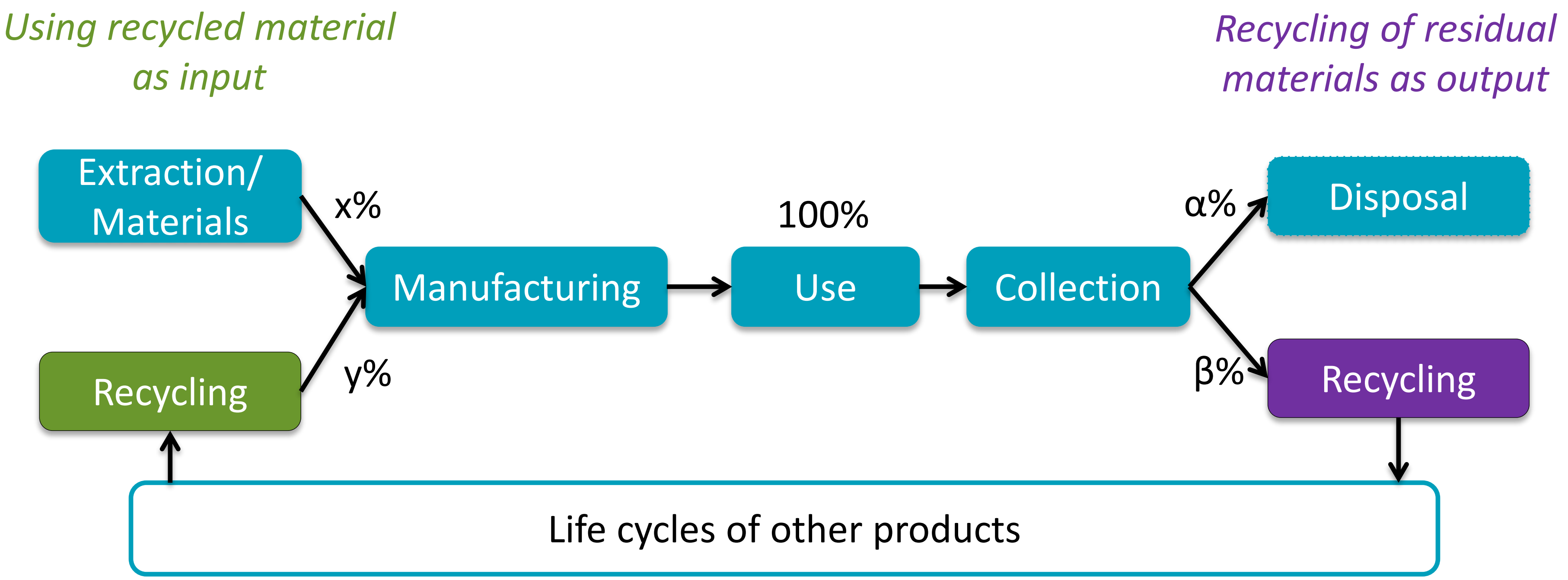
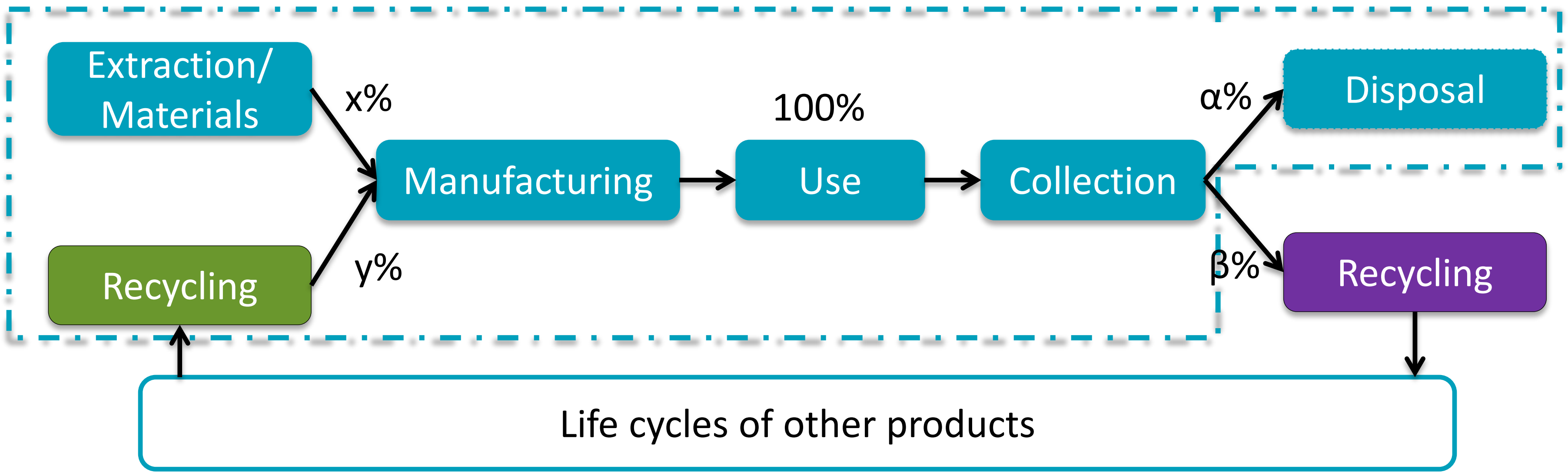
Example: description

- Let's assume a product composed of 1kg of material
  - **Is manufactured from x% virgin material and y% recycled material**
  - **At the end of its life, α% of the collected material goes to final disposal (e.g. landfill) and β% is recycled**



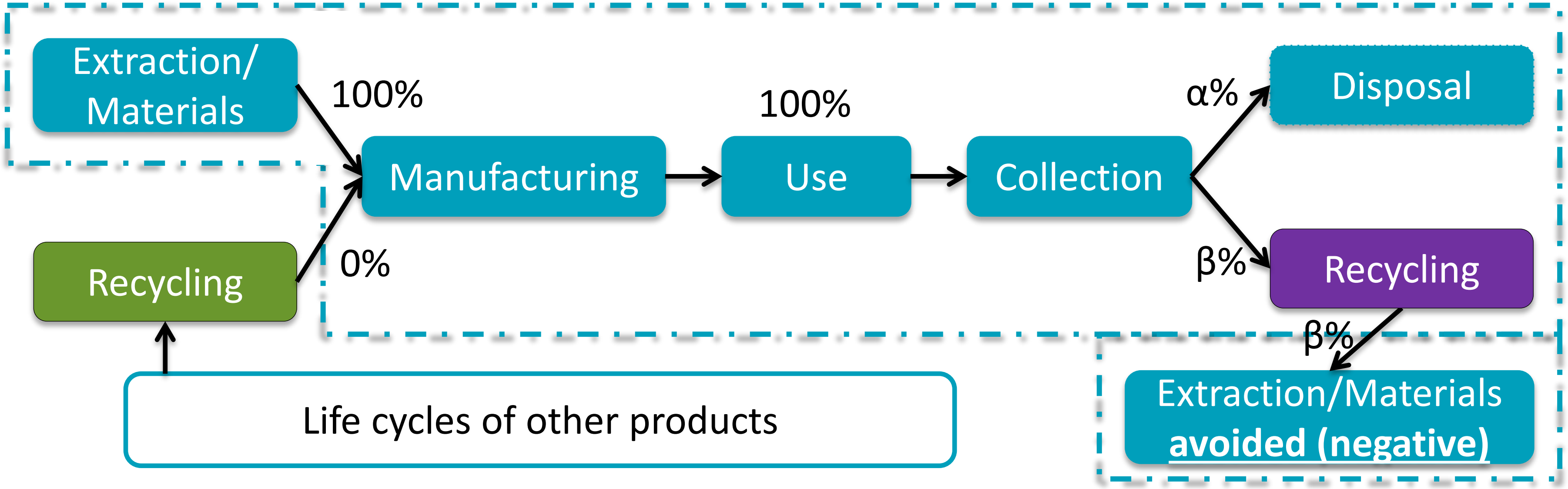
Example: “Recycled content” approach

- Recycled content approach (cut-off):
  - **Recycling impact is attributed to the life cycle that uses the recycled material**
  - **Recycling impact at end of life is simply excluded from the system (no credits, but no impacts of end of life treatment either)**



Example: "End of life recycling" approach

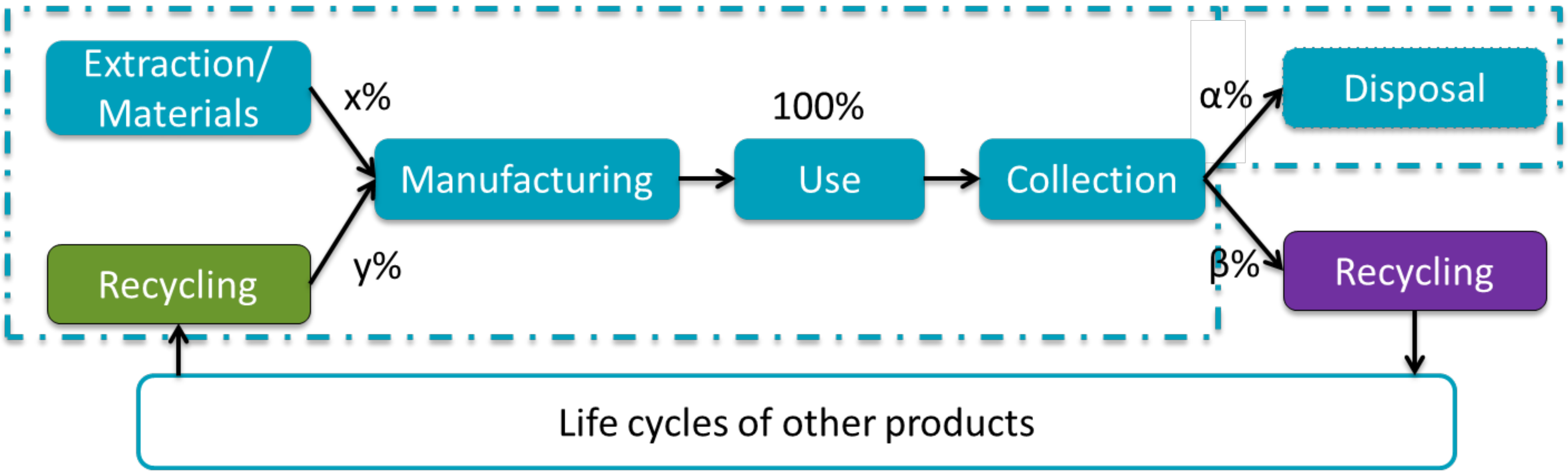
- End of life recycling approach
  - **Materials used by the life cycle are assumed as virgin, regardless of the recycled content**
  - **Recycling at the end of life avoids producing raw materials (substitution, system boundary expansion)**



Main approaches – what do they imply?

Recycled content approach:

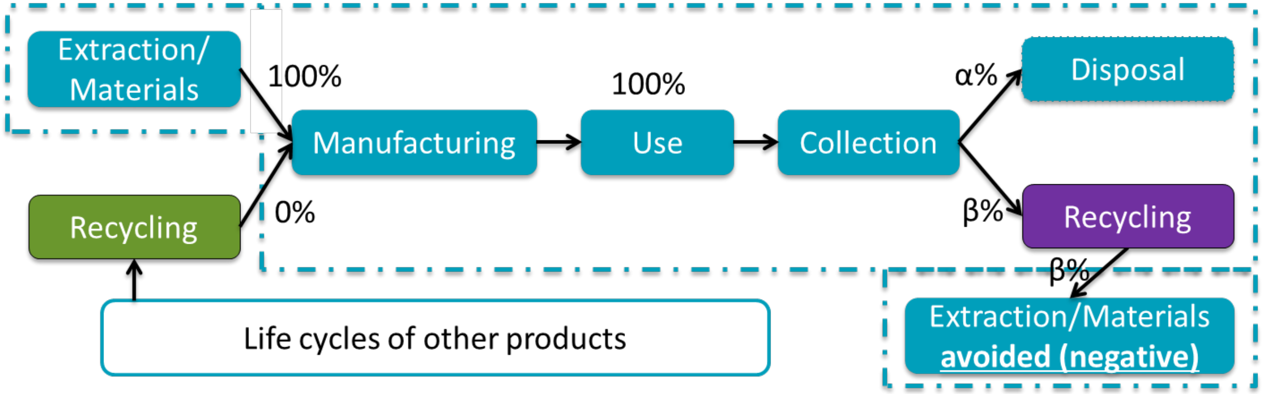
- **Boosts use of recycled materials**
  - If impacts of recycling < impacts of initial production of virgin materials
- **Encourages (though weak) recycling at the end of life**
  - Recycled material isn't associated to impacts of final disposal



Main approaches – what do they imply?

End of life recycling approach:

- **Doesn't encourage the use of recycled materials**
  - All input materials are associated to impacts of virgin materials, regardless of their recycled content
- **Encourages recycling at end of life (Design for Recycling)**
  - Recycling → « credit »
  - (must obviously take into account the modification of inherent properties of the materials)
- **Discourages dissipation of materials**
  - If they can't be collected, it's impossible to recycle them



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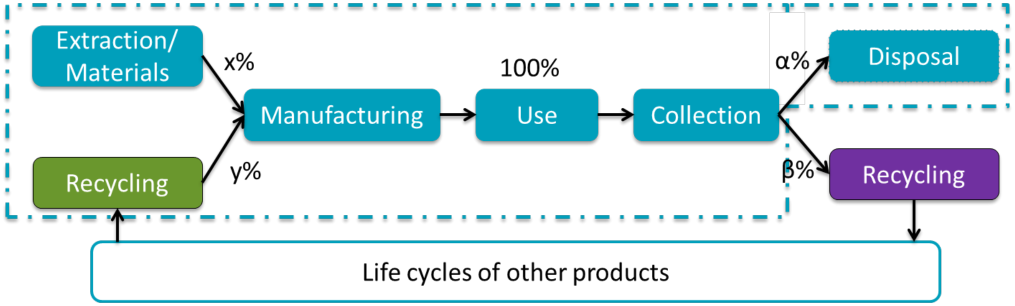
Choice of a recycling approach

*Depends on the state of the **market for recycled material***

Supply > Demand

Ex : glass in QC

Low demand, so using recycled material
→ contributes to reducing the amount of recycled material waiting to be used
→ avoids production of virgin material



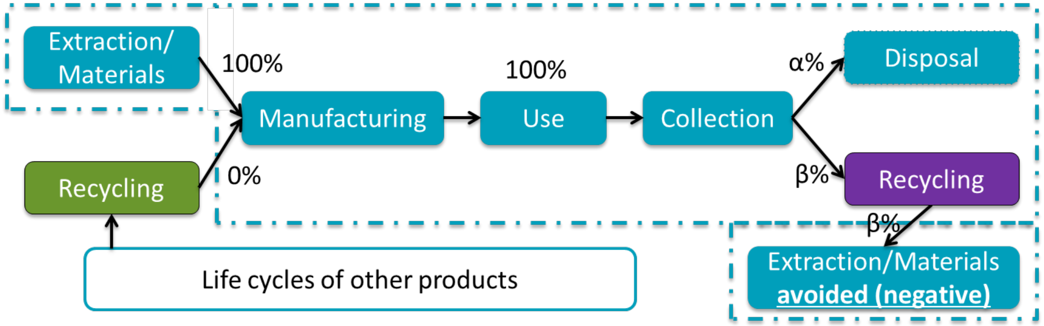
High supply, so producing recycled material
→ contributes to increasing the amount of recycled material waiting to be used
→ does not avoid production of virgin material

Recommended approach
« Recycled content (cutoff) »

Supply < Demand

Ex : steel

High demand, so using recycled material
→ deprives users of access to recycled material
→ does not avoid production of virgin material



Low supply, so producing recycled material
→ Promotes access to recycled material for other users
→ Avoids production of virgin material

Recommended approach
« End of life recycling »

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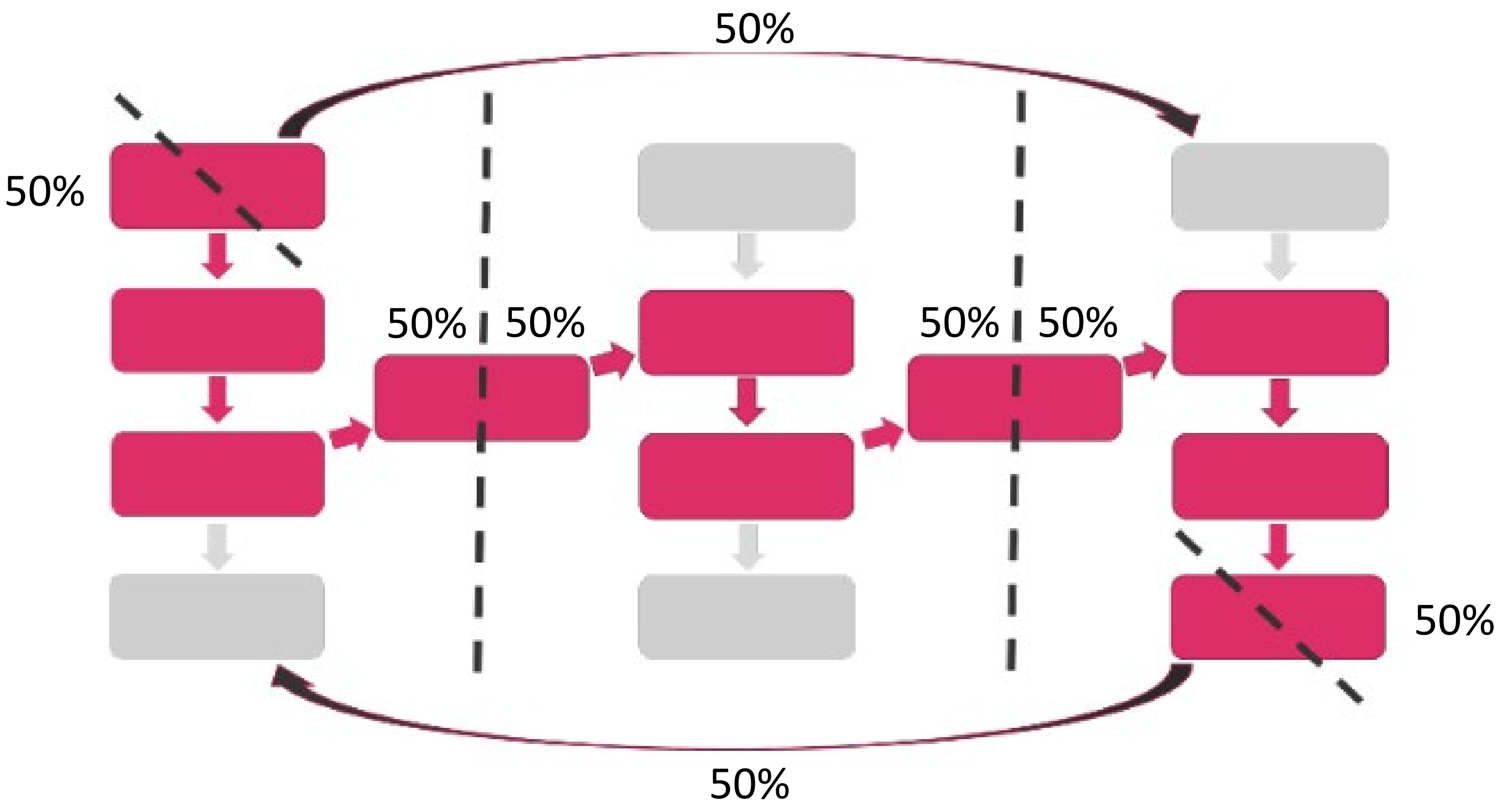
Concretely, <u>for your projects</u>

For "significant" multifunctional processes and for recycling:

- **Choose, justify and document your approach**
- **Identify the other justifiable approaches**
- **Perform a sensitivity analysis with alternative allocation approaches**

To go further in modeling recycling in LCA

50/50 Approach for recycling: The lesser of the two evils?



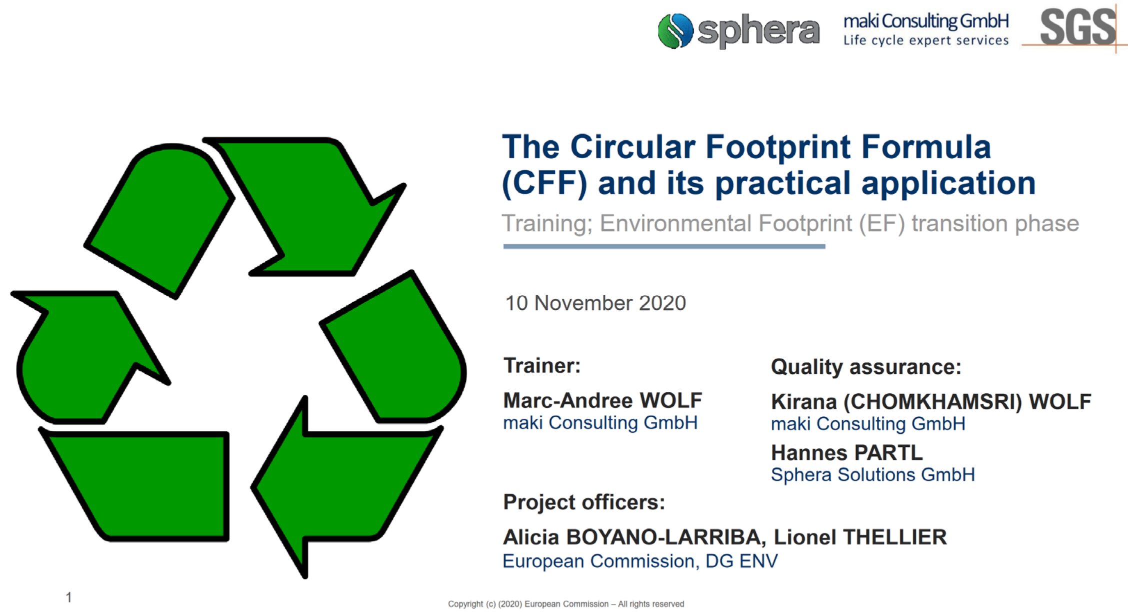
Ekvall, T., Björklund, A., Sandin, G., Jelse, K., Lagergren, J., & Rydberg, M. (2020). Modeling recycling in life cycle assessment. Retrieved from https://www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf

The PEF approach: introducing the single end-of-life formula?

Introducing the single Environmental Footprint end-of-life formula

https://pre-sustainability.com/articles/pef-series-end-of-life-modelling/

→ The Circular Footprint Formula (CFF) approach



sphera maki Consulting GmbH Life cycle expert services SGS

The Circular Footprint Formula (CFF) and its practical application

Training; Environmental Footprint (EF) transition phase

10 November 2020

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https://ec.europa.eu/environment/eussd/smgp/pdf/TrainingCFF%20Circular%20Footprint%20Formula10Nov2020_final_corr.pdf