# Consequential modelling
## -in life cycle inventory analysis

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# Overview

- LCI as a model
- The comparability algorithm: Defining the functional unit
- The linking algorithm: Composing a consumption mix
- The co-product algorithm
- Rebound effects
- Issues of time and scale
- Bringing it all together: The consequential system model
- A short history of LCA
- ISO and consequential modelling
- The role for attributional modelling
- Myths about consequential and attributional modelling
- Communicating consequential models

# LCA as a model

At the computational level, LCA is:

- a number of unit process datasets
- some algorithms for combining these datasets into models of product systems

# The consequential model

System modelling 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.

(UNEP/SETAC 2011: Shonan LCA database guidance principles)

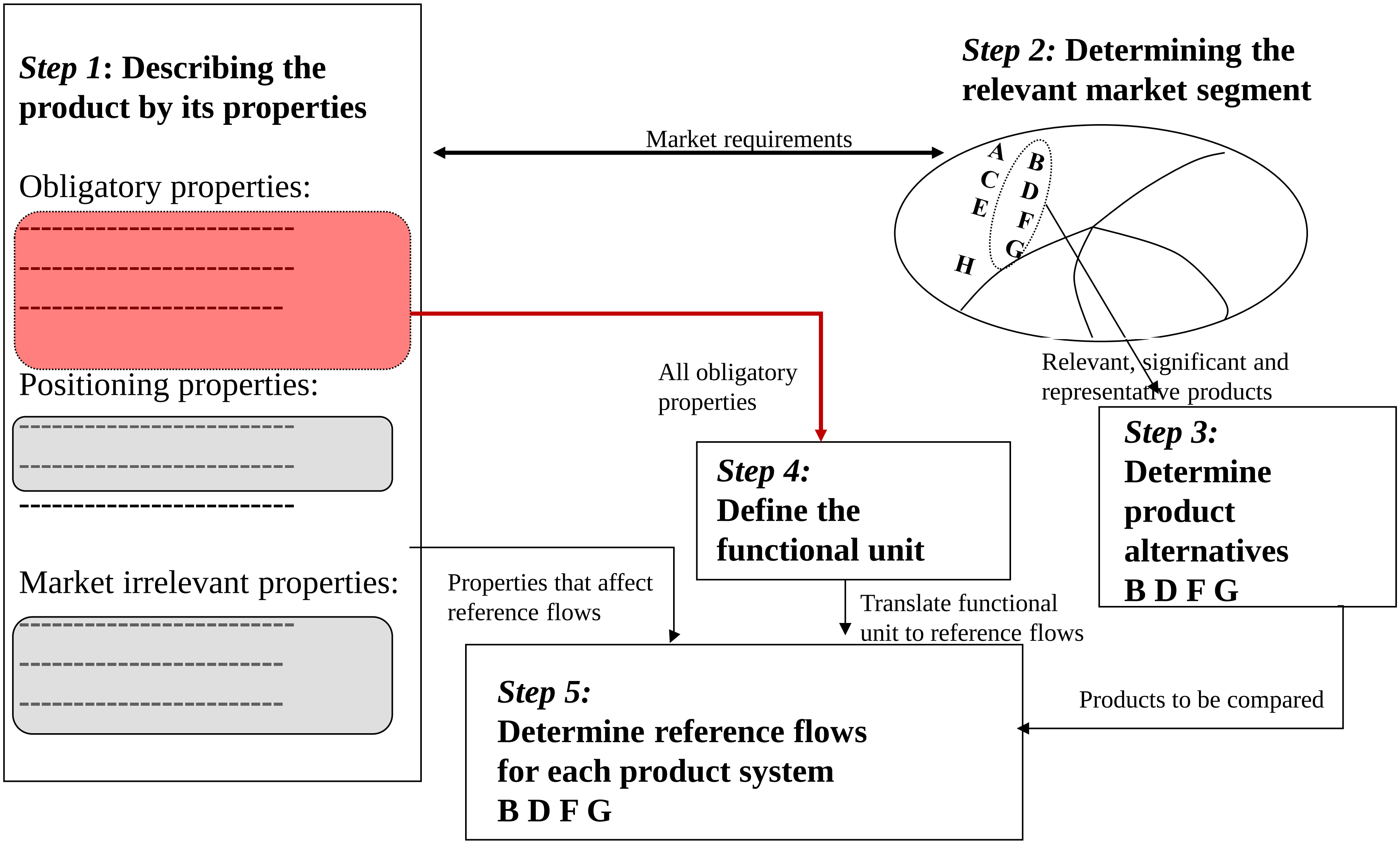
# The model algorithms

The three core aspects of LCI algorithms:

- What is comparable? Within or between product systems
- Which datasets to link? Average or marginal suppliers
- How to handle co-products?
  Partitioning (allocation) or substitution (system expansion)

# 1. The comparability algorithm: Defining the functional unit

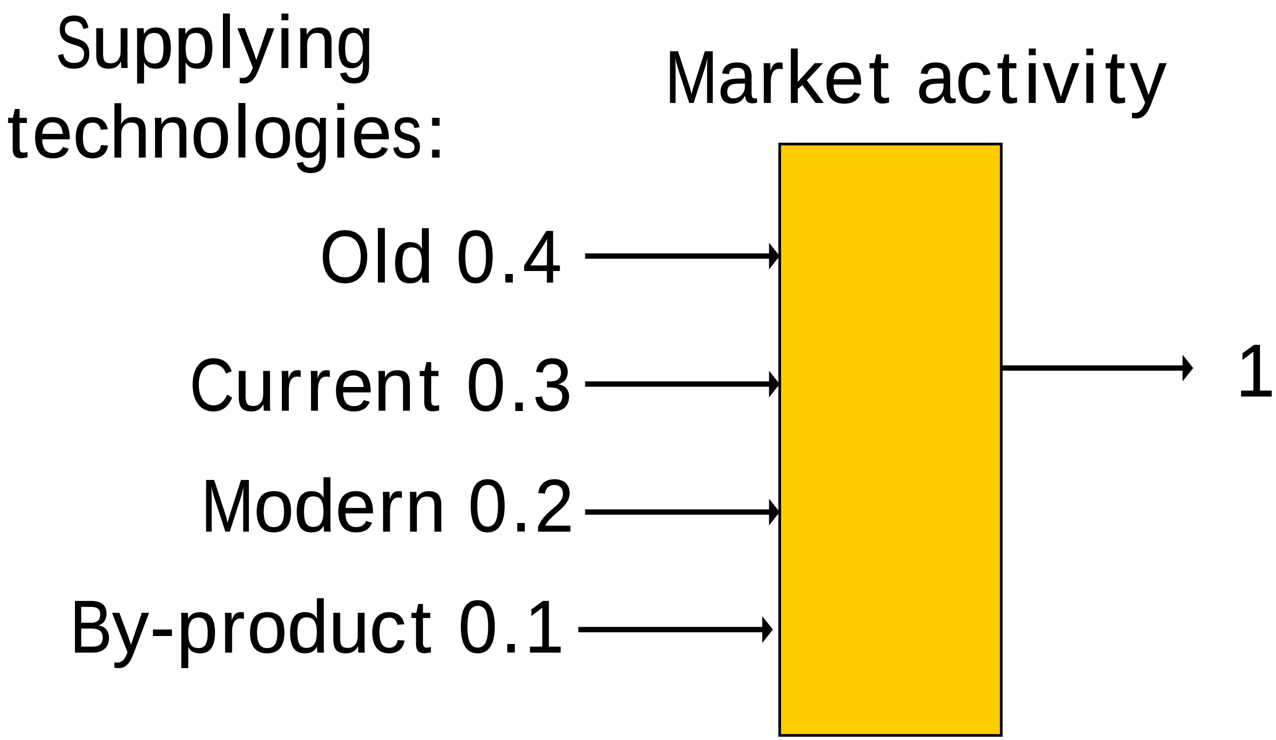
- Functional unit reflects the conditions for substitution → The functional unit is defined by the obligatory product properties on the market (segment or niche) where the product is traded, considering the size of the decision to be supported
- Markets are delimited:
  - geographically, determined by lacking or constrained imports,
  - in time, for goods that cannot be stored and for many services,
  - by customer segments, *clearly distinct with a minimum of overlap*, so that product substitution from segment to segment is unlikely (but may be sub-divided into niches between which substitution may occur)
- Segmentation must be justified




***Information flow between the five steps in the market-based procedure for product description in life cycle assessment***

*From Weidema B P, Wenzel H. (1999). A market-based procedure for product description in life cycle assessment. Poster for the 9th Annual Meeting of SETAC-Europe, Leipzig, 1999.05.25-29.*

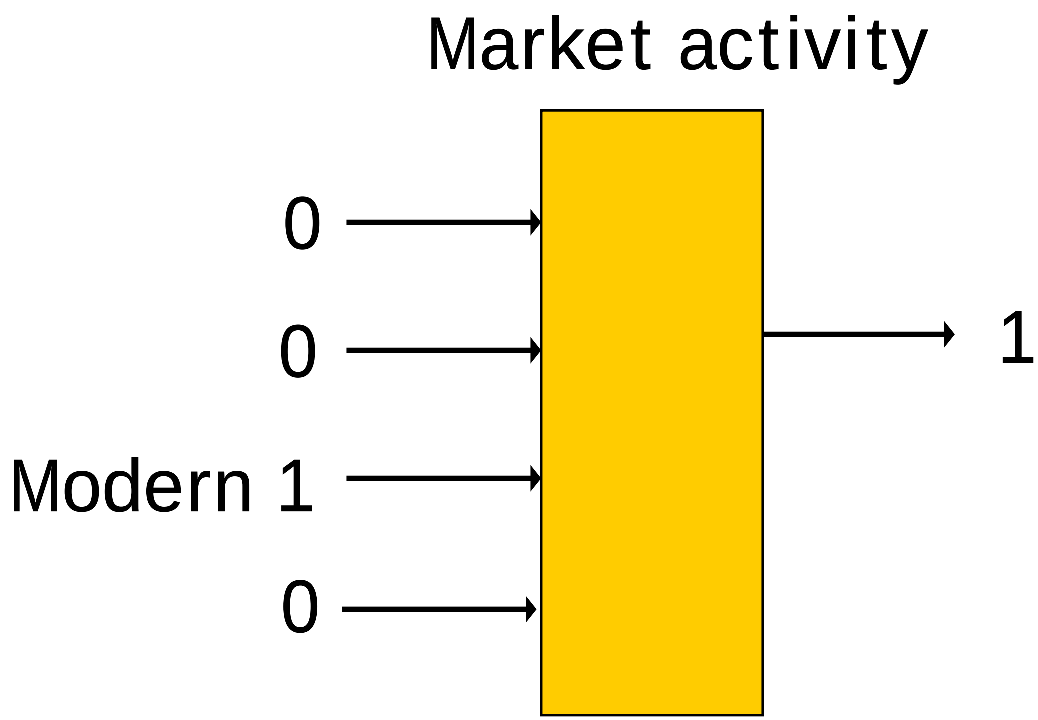
# 2. The linking algorithm: Composing a consumption mix



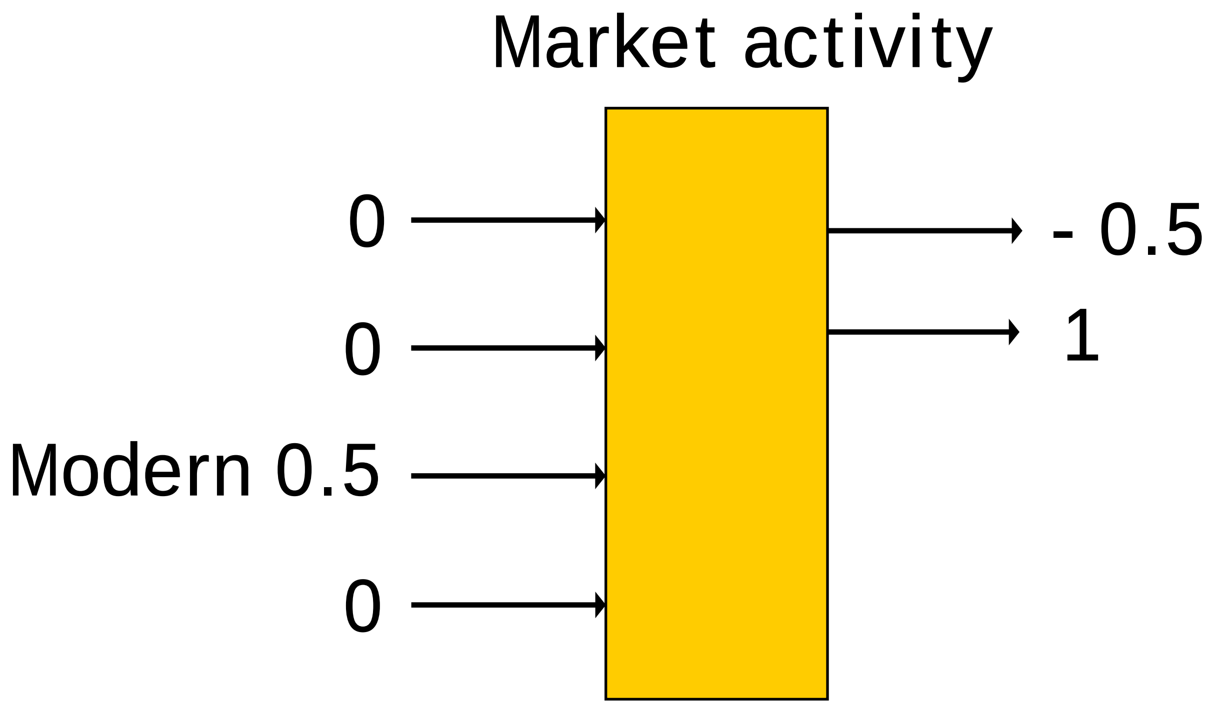
# 2. The linking algorithm: Composing a consumption mix

Marginal, unconstrained suppliers → Modern, competitive suppliers, when the product demand is generally increasing; Old, uncompetitive suppliers, when the product demand is generally decreasing (ISO 14049 - Clause 6.4) relative to the replacement rate of capital (Weidema 1993).

# 2. The linking algorithm:
# Case: Increasing market trend



# 2. The linking algorithm:
# Case: Constrained market



# 2. The linking algorithm: Composing a consumption mix

Implemented in ecoinvent v3 (consequential system model):

- By-product constraints: Only reference products (determining products) can be unconstrained.
- Technology constraints expressed via relative technology level classification (outdated, old, current, modern, new) of the individual datasets, thus making the determination subject to peer review and scientific dialogue.
- Constrained markets (when there are no unconstrained suppliers to a market): Modelled as a reduction in consumption of the marginal consumer.

# Determining product (definition)

- Product of an activity for which a change in demand will affect the production volume of the activity

    (called "reference product" in ecoinvent terminology)

# Algorithm to identify the determining product(s)

- Exclude co-products that do not provide revenue (wastes)
- When all other co-products have an alternative production route, only one of these co-product is the determining one
- Products without alternative production routes are typically determining products

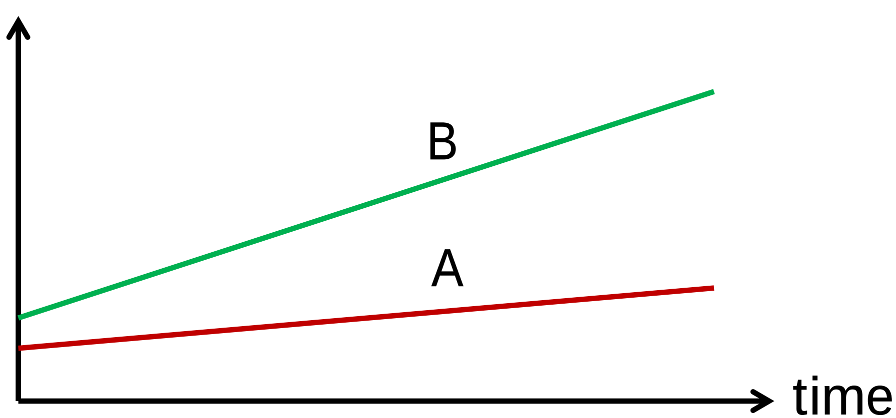
0. All have alternative production routes
    - Use relative, normalised market trend to identify the determining
1. Only one with no alternative production route
    - This is the determining product
2. More than one with no alternative production route
    - Market clearance and consumption adjustment via constrained markets

# Algorithm to identify the determining product

## When all co-products have alternative production routes

- Only one of these co-product is the determining one:
  1) Provides an economic revenue that exceeds the marginal cost of changing the production volume → the one with highest normalised market trend
  2) When only a combination fulfils condition 1) → the one with lowest normalised market trend in the combination

normalised production volume




Alternative production costs:
A: 100
B: 50
Marginal production costs:

| | | |
|---|---|---|
| | →Fulfils 1)? | |
| < 50 | → Both | → B |
| 50-100 | → Only A | → A |
| 100-150 | → Only A+B | → A |
| >150 | → None | |

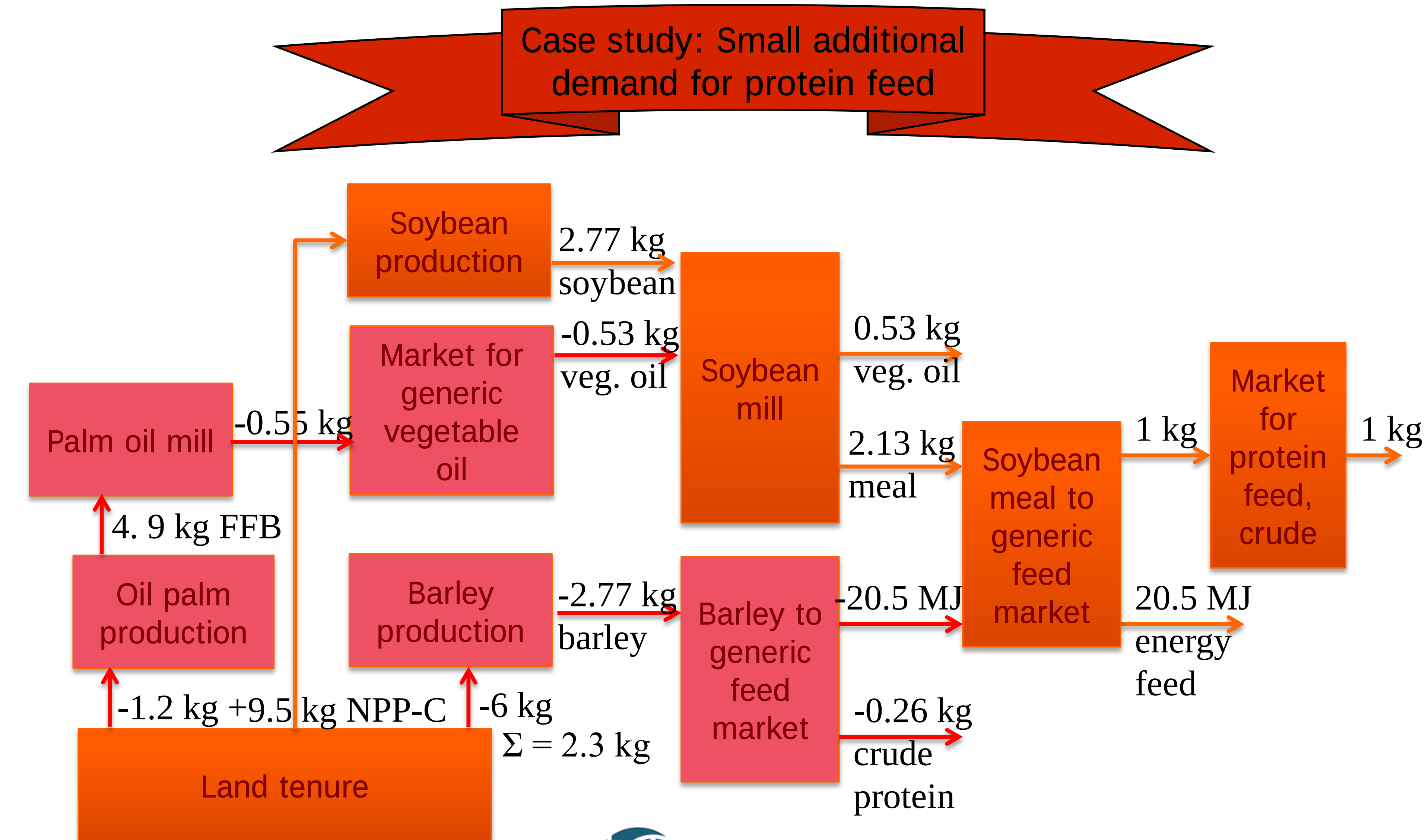
# The co-product algorithm

Follows consistently the first priority of the ISO 14044 hierarchy: Subdivision for combined production and substitution (system expansion) for joint production.

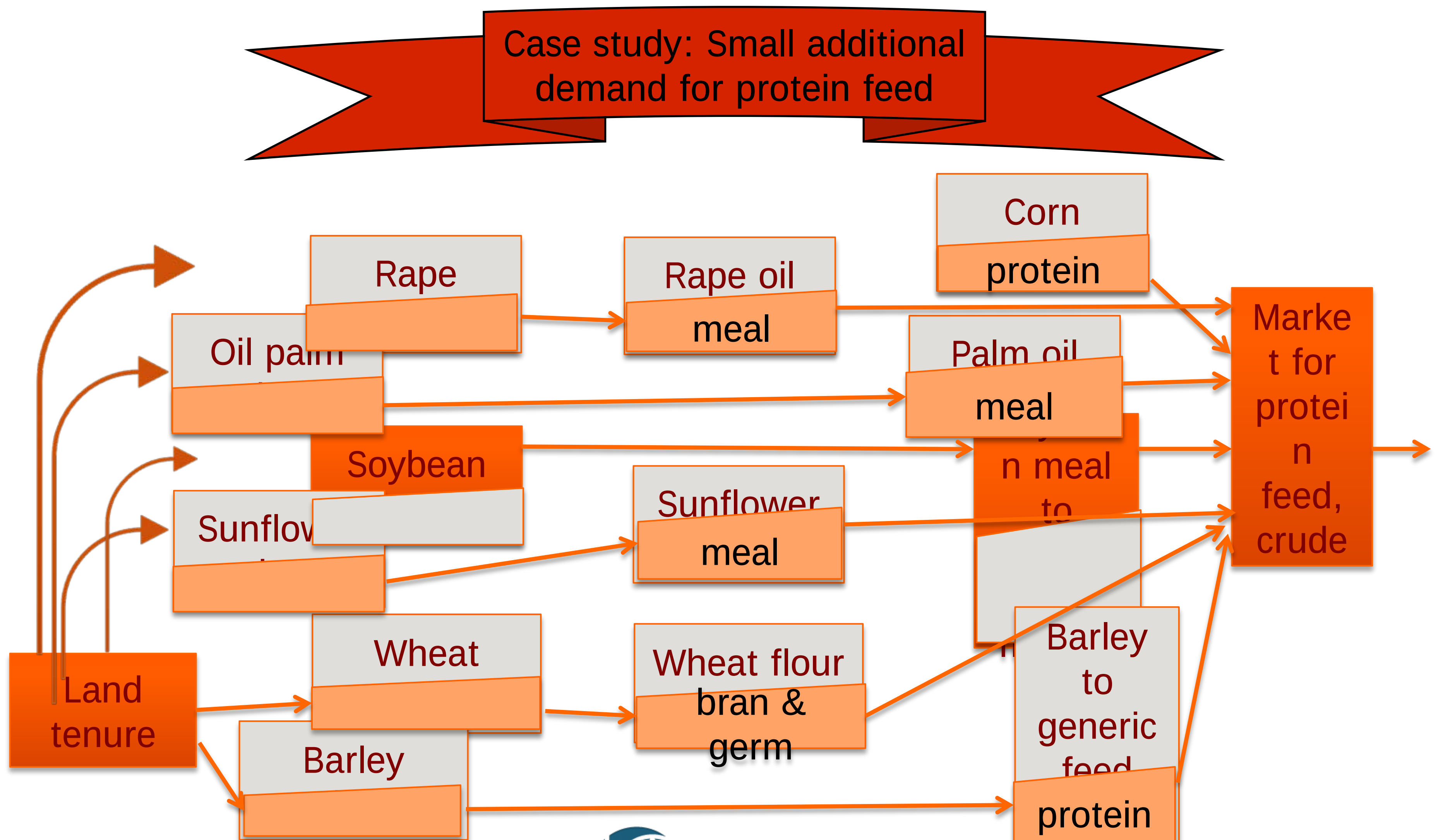
Substitution shown by Suh et al. (2010) to be mathematically identical to the by-product technology model of Stone (1960), clarifying the simplicity of the algorithm: By-product outputs are modeled as negative inputs.


What is substituted is the inputs to the market that the negative input is linking to → Justification of what is substituted is already given by the comparability and linking algorithms.

# The co-product algorithm



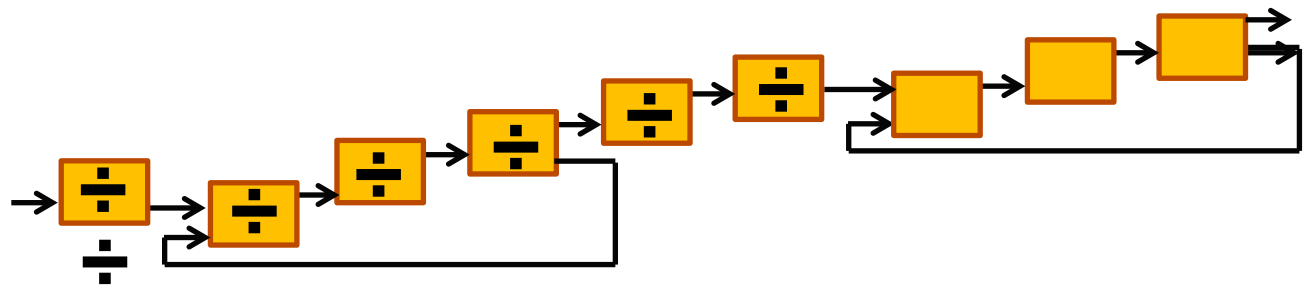
# To compare: An attributional system



# The co-product algorithm

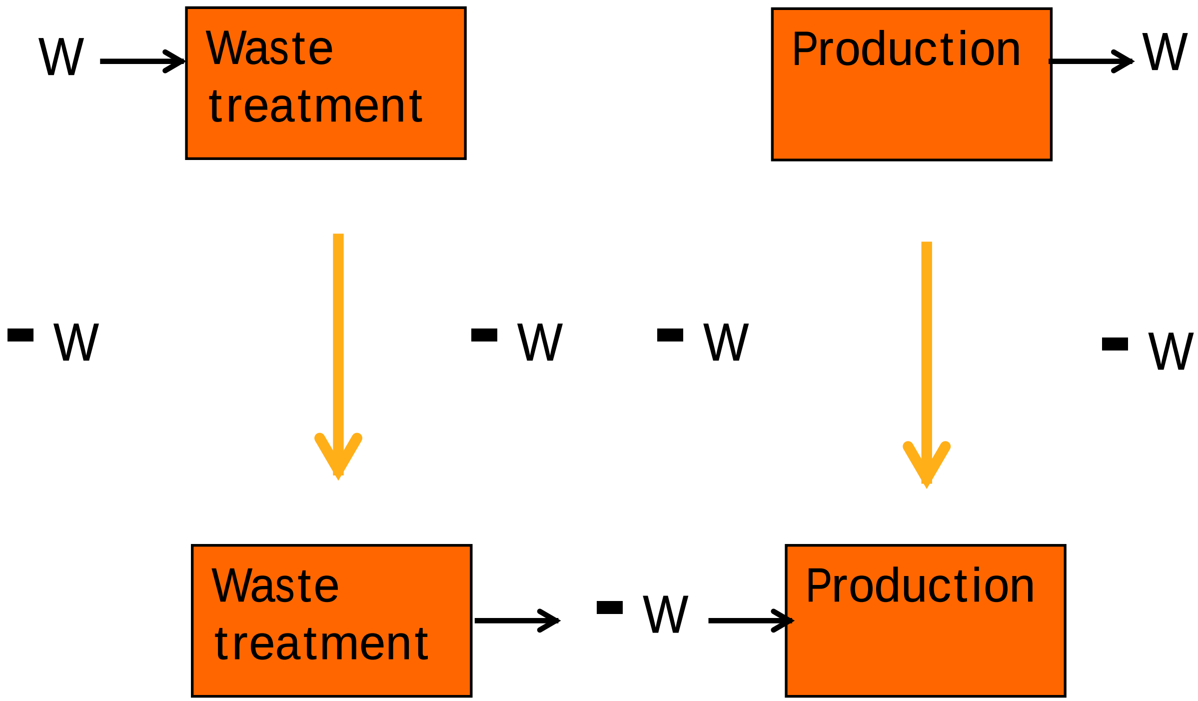
Substitution shown to be the only algorithm that consistently maintains mass, elementary, energy and monetary balances of the resulting single-product systems, since all activities remain intact and are simply scaled up or down (Weidema & Schmidt 2010).

# Mass balance as a sanity check



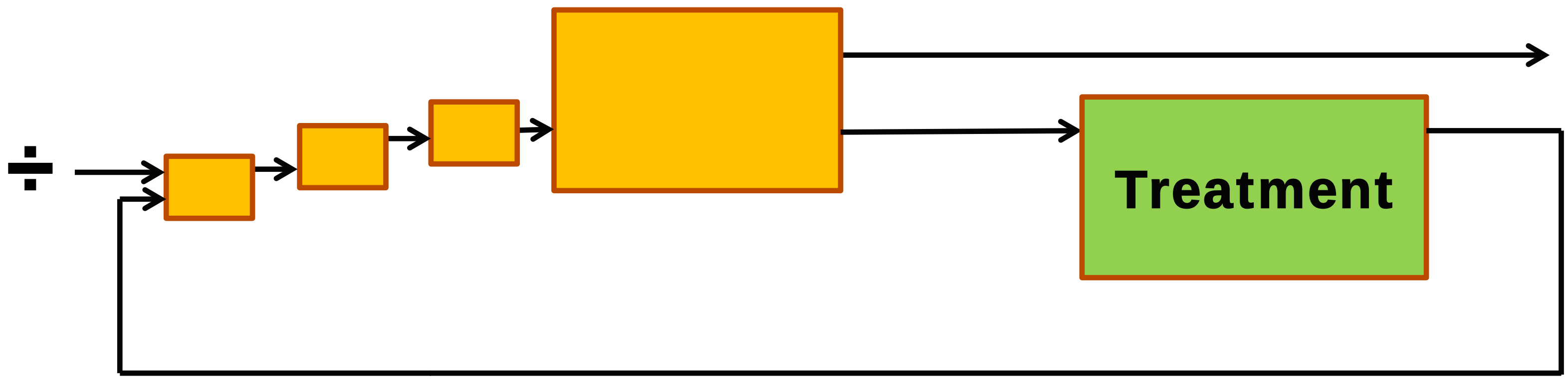
- When substituting, no activities are partitioned
- The level of each activity is simply adjusted up or down to accommodate the output requirements
- The mass balances of each activity and of the entire system are preserved

# The use of negative product flows




- An input can be modelled as a negative output
- An output can be modelled as a negative input
- Allows to maintain mass balances when modelling the physical and economic causality for materials for treatment

# Substitution or system expansion?




- The term ”system expansion” implies that your original system was incomplete
- ”Substitution” is a more general term and the most appropriate when your initial system is already complete
- In practice, the terms are used as synonyms

# The co-product algorithm
(Stepwise procedure for system expansion)

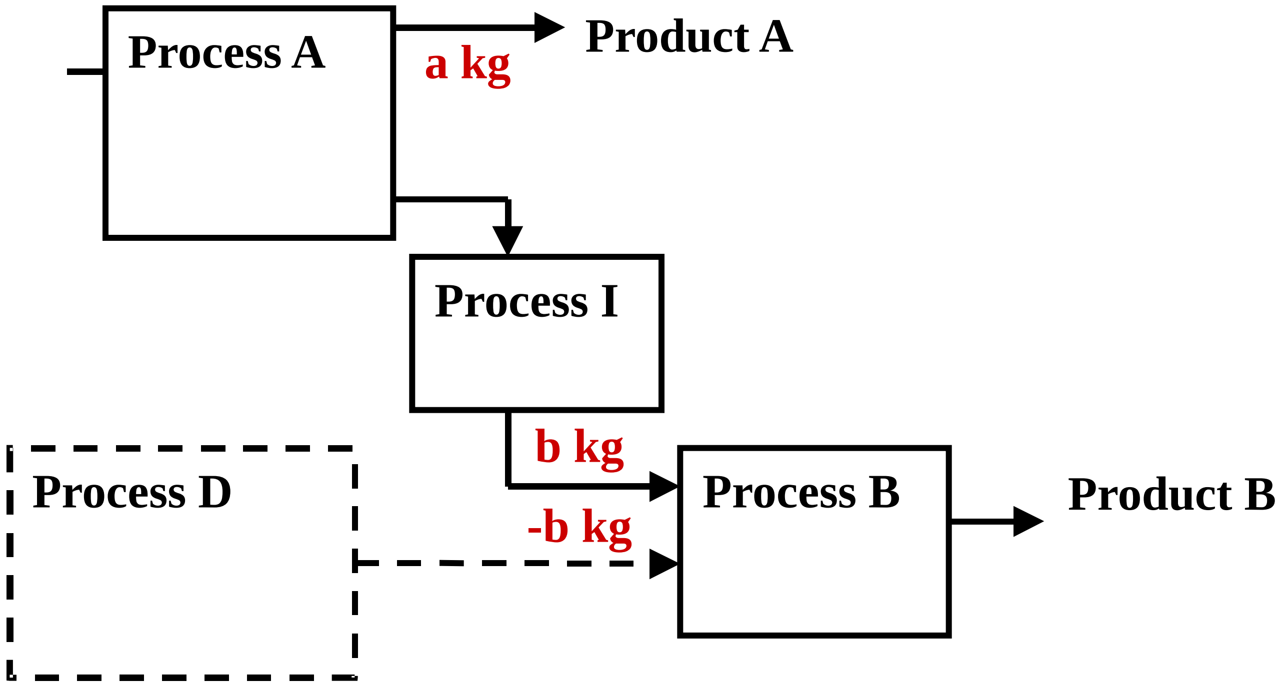
1. Combined or joint production?
   - Can the co-products be independently varied?

For joint production:

2. What is the determining product?

3. Is the dependent product fully utilised?

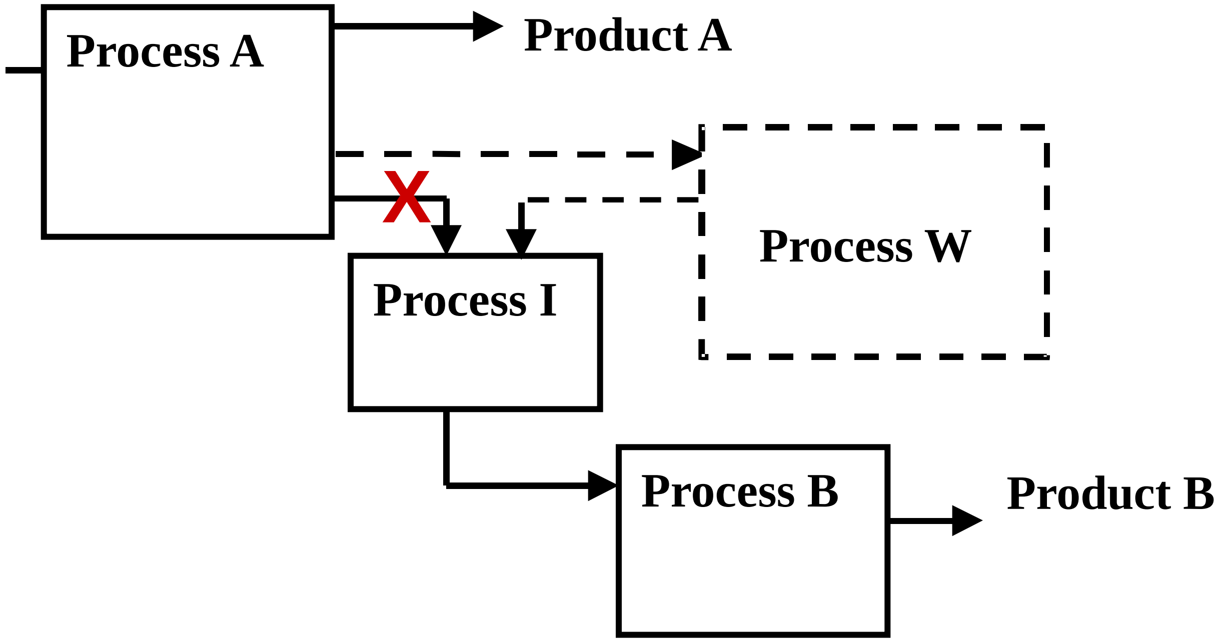
# Substitution
## (full utilisation of dependent co-product)




| | |
|---|---|
| Product A is ascribed process: | A+I-D |
| Product B is ascribed process: | D+B |

+ ΔB downstream

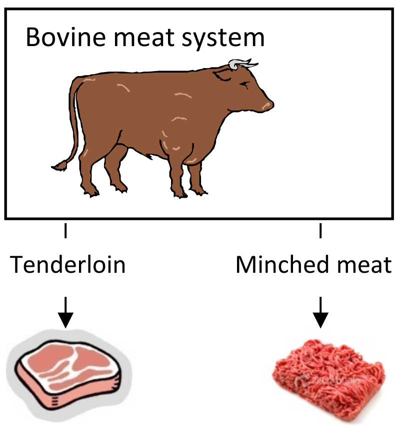
# Substitution
## (not full utilisation of dependent co-product)

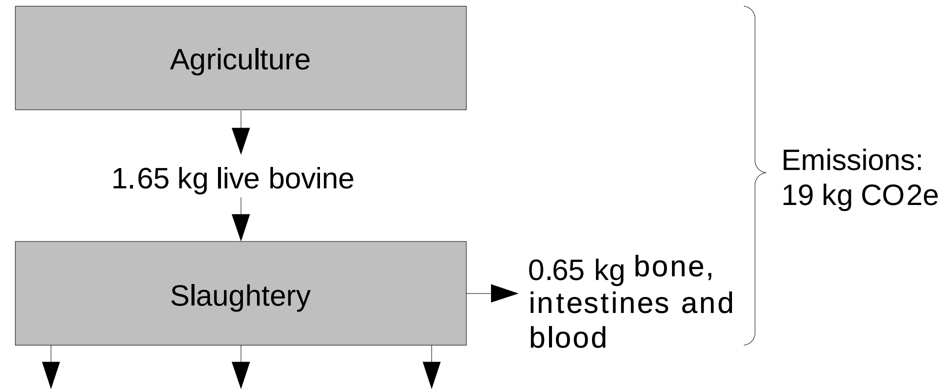



| | |
|---|---|
| Product A is ascribed process: | A+W |
| Product B is ascribed process: | I+B-W |

# When more than one co-product have no alternative production route

- Products without alternative production routes are typically determining products






**Compare result (37 kg CO2e) with economical allocation!!!**

| Co-product | Tenderloin | Fillet | Other |
|---|---|---|---|
| Mass output | 0.043 kg | 0.142 kg | 0.815 kg |
| Price | 30 USD/kg | 20 USD/kg | 13.9 USD/kg |
| Economical output | 8.4% | 18.4% | 73.2% |

> Prices adjust until market is cleared (all products are sold)

> Demand for 1 USD cause increase in production volume of 1 USD

> Thus demand for 1 kg tenderloin causes production of 8.4% of 1 kg
= 0.084 kg tenderloin

> Total change in production volume:
= 0.084 kg tenderloin + 0.277 kg fillet + 1.591 kg other = 1.953 kg

> Demand for 1 kg tenderloin causes output from slaugterhouse at 1.953 kg
Emission per kg is 19 kg CO2e
Emissions per 1.953 kg is = 1.953*19 = 37 kg CO2e

> Correction in use stage 1 kg tenderloin (only 0.084 kg produced):
Other users have to use less tenderloin and more fillet + other

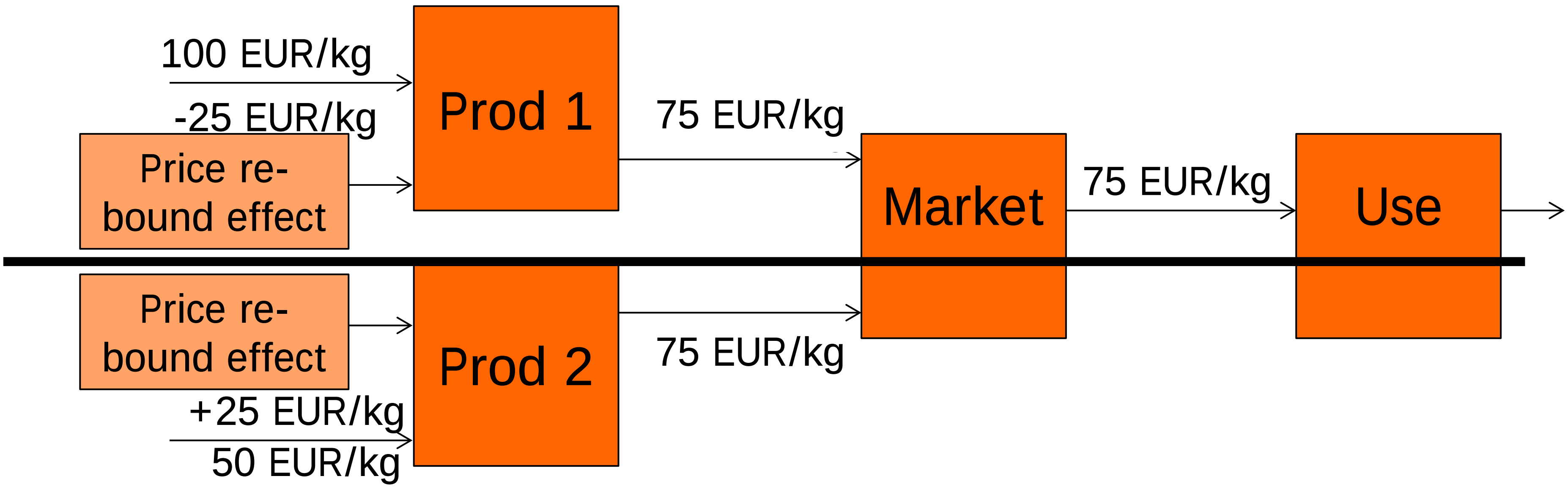
# Inclusion of first-order rebound effects

- Rebound effects are the derived changes in production and consumption when the implementation of an improvement option liberates or binds a scarce production or consumption factor such as:
  - money (when the improvement is more or less costly than the current technology),
  - time (when the improvement is more or less time consuming than the current technology)
  - space (when the improvement takes up more or less space than the current technology), or
  - technology (when the improvement affects the availability of specific technologies or raw materials).

# Example: Price rebound effects

- Liberated consumer money will be used for other products - and money can only be spent once
- Price elasticities show how liberated money are spent, or where savings are made
- 35% own price elasticity of meat: If price increases by 1%, consumption of meat will decrease by 0.35% (specific price rebound); the rest of the price change will result in decreases in other products (general price rebound, on average or marginal spending)
- Ignoring price rebound effect leads to underestimating the sustainability effect of technologies that involve economic costs – and overestimating the effect of technologies that involve a cost saving

# The balance argument for rebound effects




Without including the price rebound effect, the individual product systems would not be balanced

# Examples: Time and space rebound effects

- Time: Time elasticities (Coefficients of time allocation when more or less time becomes available) are scarce. Some indications that shifts mainly occur within work and leisure activities, not between them.
- Shifting in the timing of activities: Day-time shopping, night-time Internet shopping. More flexibility leads to more outgoing activities.

- Space: Liberated road space is filled 50-90% by increased traffic. Agricultural land constraints lead to pressure on nature.

# Examples: Technology rebound

- Technology:
  - Wider applications than foreseen
  - Reducing or increasing use of other technologies: Car ownership / car driving
  - Raw material constraints: Fish constraints lead to reduced consumption of omega-3 fatty acids

- In general, ignoring rebound effects leads to either under- or over-estimation of the effects of new technologies. This stresses the need to assess new technologies from an overall cost-benefit perspective, including rebound effects.

# Time horizon:
# Short and long term marginal technologies

- Short-term: Changes in capacity utilization only
- Long-term: Capacity changes
- Short-term decisions have both:
  - short-term consequences
  - long-term consequences (on investments)
- Long-term consequences last longer and dominate the overall impacts of a decision
- Long-term marginal technologies are more stable than the average

# Scale of change

- Small-scale: A change that does not affect the determining parameters of the overall market situation, i.e., the direction of the trend in market volume and the constraints on and production costs of the involved products and technologies.
- Large-scale: A change that affects the determining parameters of the overall market situation, i.e. the direction of the trend in market volume OR the constraints on OR production costs of the involved products or technologies.

# Scale of change: Small changes with large effects

- Large, long-term changes may be the consequence of the sum of many small decisions
- Small decisions have both:
  - small, short-term consequences
  - long-term consequences
- Consequential modeling is as relevant for small decisions as for larger decisions

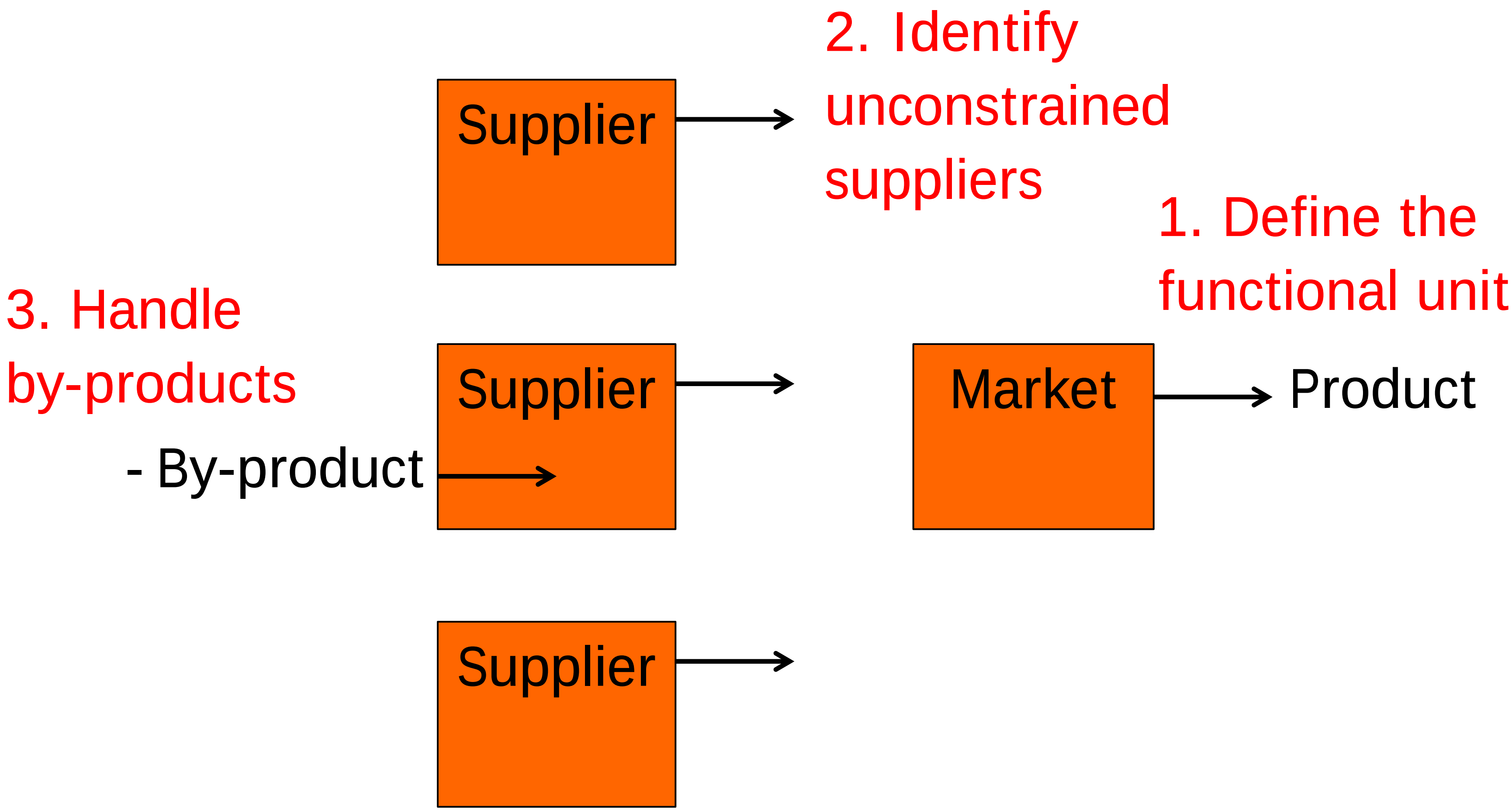
# Scale of change:
# Small changes with large effects

# Exercise: Bringing it all together - The consequential system model

Choose a product (group):

- Protein feed
- Generic vegetable oil
- Land tenure
- Leather
- Your own product?

# Exercise: Bringing it all together
# - The consequential system model



# Early roots of consequential LCA modelling

- Early 1990's analysis of improvements in efficiency of heat and electricity generation: Discussion of the allocation problem and the impacts from decisions
- Impacts to be allocated per additional useful unit produced
- Impact from marginal technologies: ”the technology which is taken into use or taken out of use if the produced amounts are increased or reduced, respectively”


- Heintz B & Baisnée P-F. (1991). System boundaries. In: Life cycle assessment. Workshop report, Leiden, The Netherlands, 2-3 December 1991. SETAC, Brussels, Belgium, pp. 35-52.
- Pedersen B (1993). Environmental Assessment of Products. Helsinki: UETP-EEE.
- Weidema B P (1993). Market aspects in product life cycle inventory methodology. Journal of Cleaner Production 1(3-4):161-166.
- Weidema B P, Nielsen A M. (1998). Identifying marginal technologies for inclusion in inventories for comparative life cycle assessments*.* Presentation for the 8th SETAC-Europe Annual Meeting, Bordeaux, 1998.04.14-18.
- ISO 14041:1998 and ISO 14049:1998

# Early roots - Input-Output analysis

- Discussion on by-products:
  - Industry technology model (= economic allocation)
  - Commodity technology model (= substitution)
  - By-product technology model (= system expansion) suggested by Stone R. (1960): Input-Output and National Accounts. Paris: OECD.
- Commodity/By-product models generally accepted as the most correct. The resulting negative values less palatable for statisticians ➔ Industry technology model still used in some countries.

Suh S, Weidema B P, Schmidt J H, Heijungs R. (2010). Generalized Make and Use Framework for Allocation in Life Cycle Assessment. Journal of Industrial Ecology 14(2):335-353.

# The origin of the terms attributional and consequential

- International Workshop on Electricity Data for Life Cycle Inventories, Cincinnati, 2001.10.23-25.
- UNEP/SETAC (2011). Shonan LCA database guidance principles:
  - **Attributional approach**: System modelling 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**.
  - **Consequential approach**: System modelling 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.

Attributional

Accountancy

Retrospective

Status-quo

Descriptive

Prospective

Change-oriented

Consequential

Effect-oriented

Comparative

# ISO 14040/44: A standard for consequential LCA

- “LCA can assist in
  - identifying opportunities to improve the environmental performance of products at various points in their life cycle,
  - informing decision-makers (...), e.g. for the purpose of strategic planning, priority setting, product or process design or redesign,
  - the selection of relevant indicators of environmental performance,
  - marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).”

(ISO 14040:2006 – Introduction)

# ISO 14040/44:
# A standard for consequential LCA

## “Priority of scientific approach”

“Decisions within an LCA are preferably based on **natural science**. If this is not possible, **other scientific approaches** (e.g. from social and economic sciences) may be used or international conventions may be referred to. If neither a scientific basis exists nor a justification based on other scientific approaches or international conventions is possible, then, as appropriate, decisions may be based on **value choices**.”

(ISO 14040:2006 – 4.1.8 Principles for LCA)

# ISO 14040/44:
# A standard for consequential LCA

- The allocation hierarchy:
  - The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure:
  - 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, (…)

- Allocation clause ends with a reference to ISO 14049

# ISO 14049

- “The supplementary processes to be added to the systems must be those that would actually be involved when switching between the analysed systems. To identify this, it is necessary to know:
- whether the production volume of the studied product systems fluctuate in time (in which case different sub-markets with their technologies may be relevant), or the production volume is constant (in which case **the base-load marginal is applicable**),
- (...) whether (...) the inputs are delivered through an open market, in which case it is also necessary to know:
- whether any of the processes or technologies supplying the market are **constrained** (in which case they are not applicable, since their output will not change in spite of changes in demand),
- which of the unconstrained suppliers/technologies has the highest or lowest production costs and consequently is **the marginal supplier / technology** when the demand for the supplementary product is generally decreasing or increasing, respectively.” (ISO 14049 - Clause 6.4)

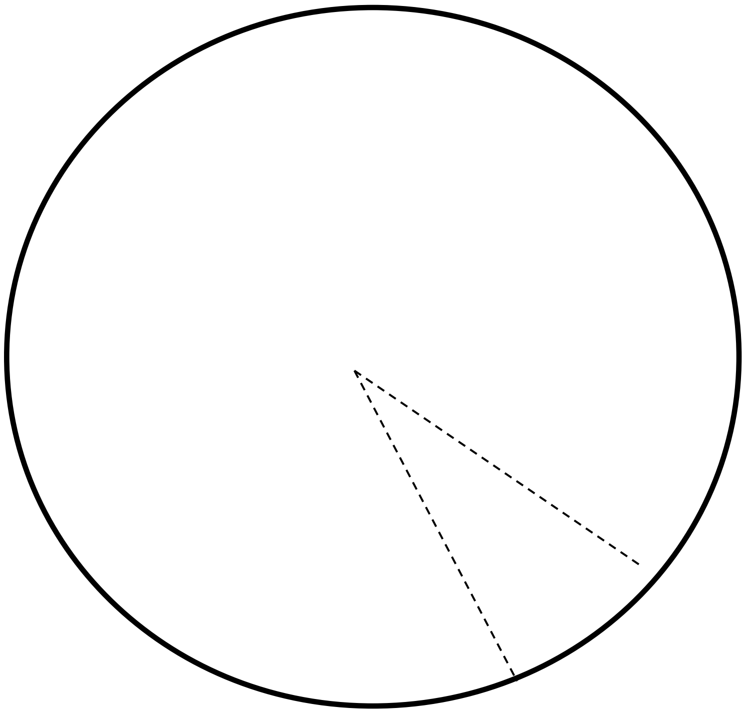
# ISO 14040/44:
# A standard for consequential LCA

- The allocation clause 4.3.4.2 ends:

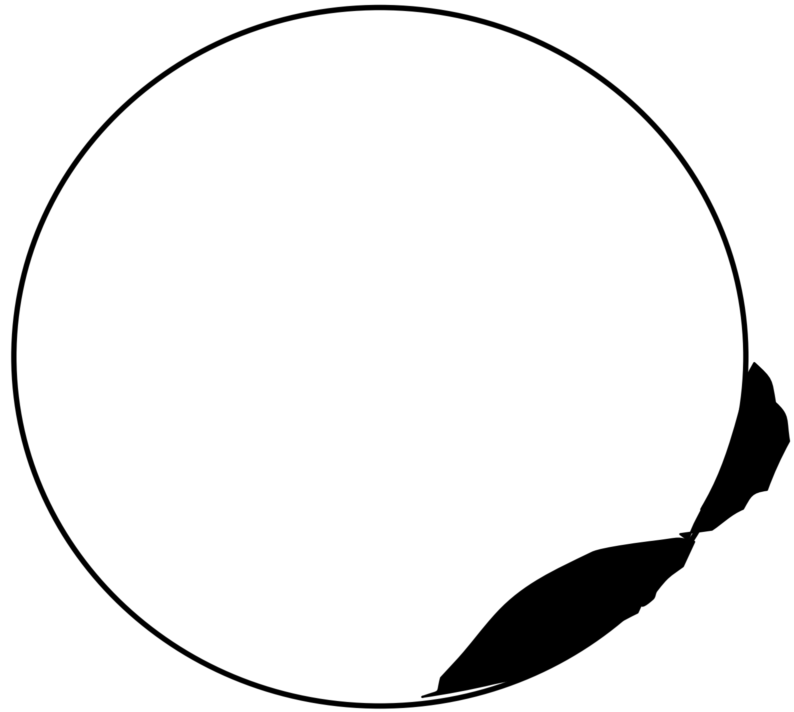
  *"The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input-output relationships and characteristics."*

  Only consequential models maintain mass (and other) balances intact during inventory calculation

# Attributional or consequential?



Attributional



Consequential

# Attributional or consequential?

| Attributional | Consequential |
|---|---|
| Non-comparative, i.e. no requirements to functional unit | Functional unit based on conditions for substitution |
| Rule-based system boundary, e.g. according to economic value | System includes all processes affected |
| Rule-based allocation, e.g. according to economic value | ISO compliant: Allocation avoided by substitution |

# A role for attributional LCA?

- Studies at a societal level, where the entire environmental impact of all human activities is studied, with the aim of identifying areas for improvement, disregarding whether such improvements shall be sought through product-oriented policies or through direct regulation of the individual activities.
- Studies that seek to avoid blame or to praise or reward for past good behaviour, for example avoiding blame that a specific deplorable activity, such as slavery, occurs in the product system, or rewarding producers that have invested in a praiseworthy technology such as solar power.
- Studies on environmental taxation, where the focus is less on the consequences of the tax, but rather on who is to carry the burden.

- Is LCA relevant for these purposes at all?

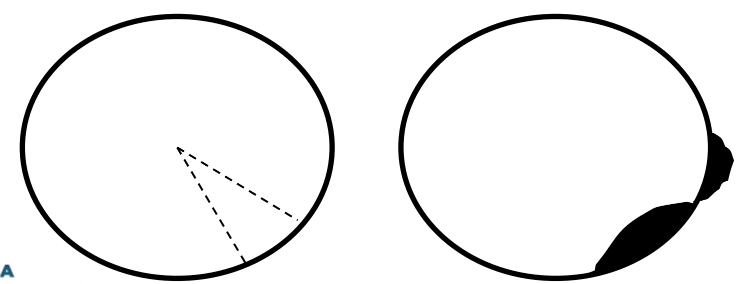
# Consequential modeling - the theoretically most appropriate choice, but…?
# Myths about attibutional and consequential:

- "attributional models are closer to current reality"
- "consequential models requires more data"
- "consequential models are more costly"
- "consequential models are more uncertain"
- "attributional models are simpler"
- "attributional models are easier to communicate"
- "consequential models are difficult to reproduce"
- "consequential models are less relevant for small changes"
- "attributional models are more stable over time"

# The confusion of model with reality

- ILCD Handbook:
  - ”to reflect the existing physical reality of an existing supply chain (attributional modelling)”
  - “In attributional modelling the life cycle of the system is modelled as it is”

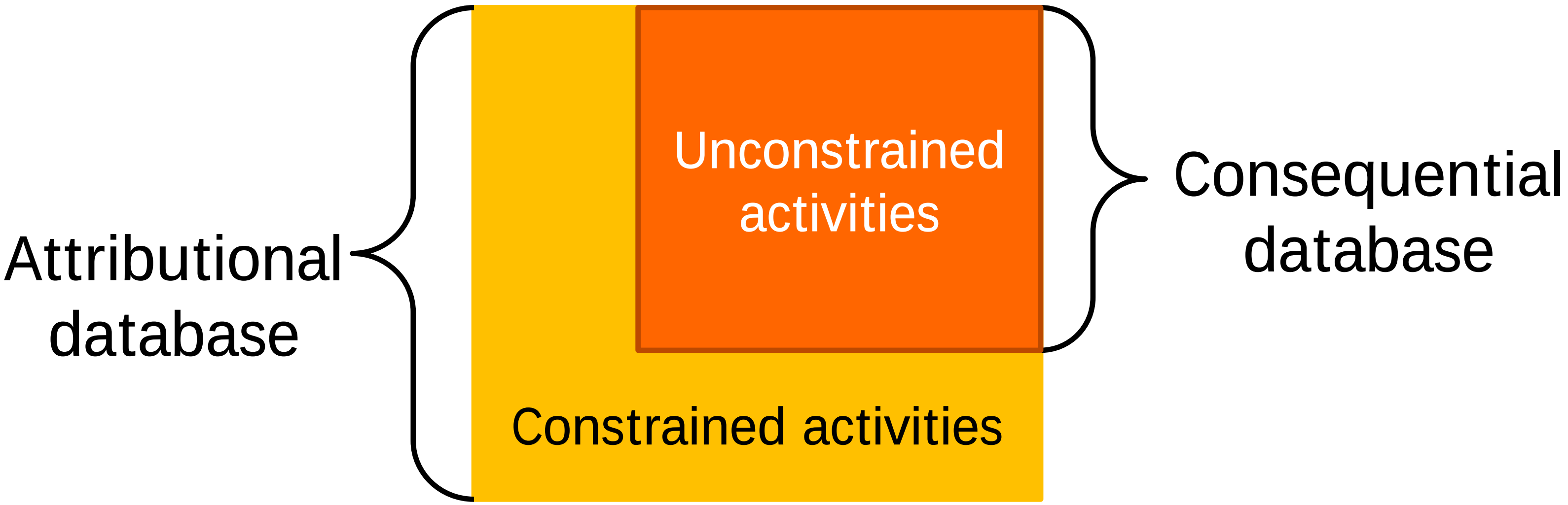
- Only unlinked, unallocated activity datasets reflect and can be validated against their real-world counterparts.
- As soon as you wish to isolate a linked product system, you need a model with modelling assumptions. Product systems do not exist in the real world.



# The confusion of model with reality

- Modeling may be based on normative assumptions (attributional) or market assumptions (consequential).
- UNEP/SETAC (2011). Shonan LCA database guidance principles (in editing):
  - **Attributional approach**: System modelling 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**.
  - **Consequential approach**: System modelling 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.
- Subjectivity and normative choices in modelling versus openness to scientific challenge and validation.

# Why are data requirements lower in a consequential model?

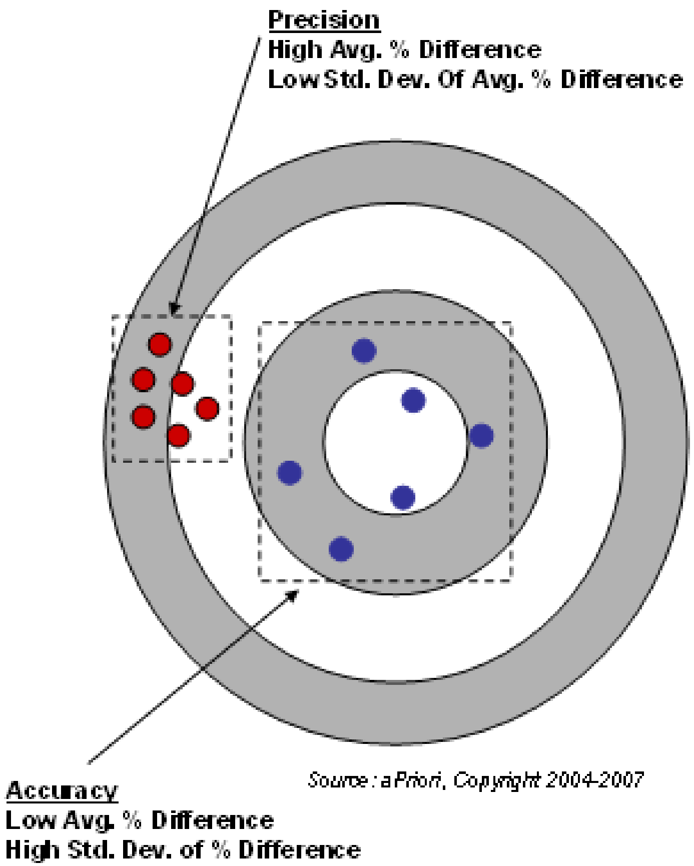



- At the same level of detail, a consequential LCA has a lower data requirement

# Why is consequential modeling less costly?

- Cost of LCA is mainly determined by cost of primary data collection
- Data requirement for consequential models is lower

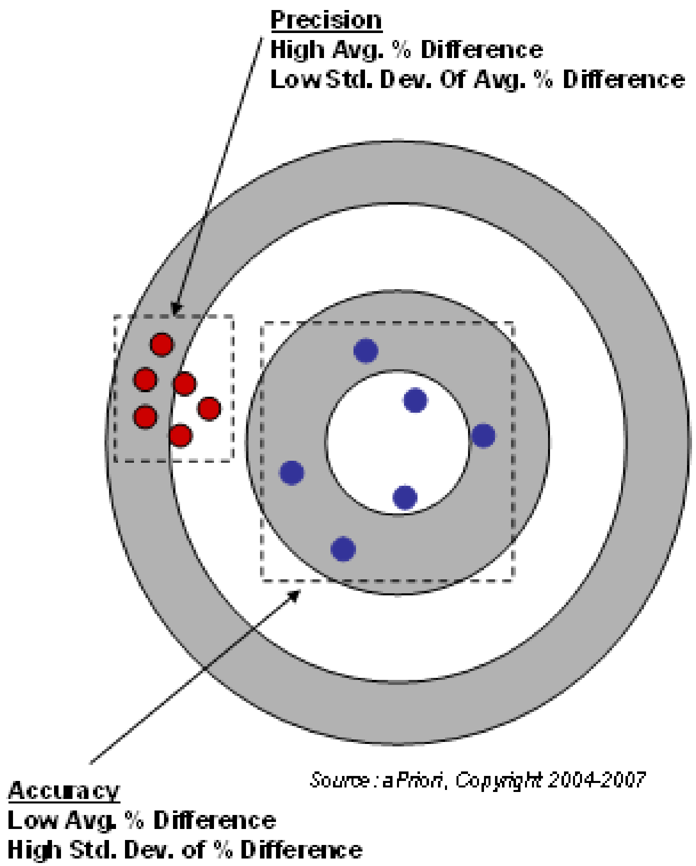
# Precision and accuracy: Why are consequential model results less uncertain?




Accuracy and Precision

- Main source of uncertainty in consequential models is the actual variability and lack of precision in the underlying data.
- In attributional models, the main source of uncertainty is the bias introduced by the lack of accuracy in the method, i.e. that the average data and use of allocation leads to a result that does not reflect the actual consequences of the decision studied.

# Precision and accuracy: Why are consequential model results less uncertain?




Accuracy and Precision

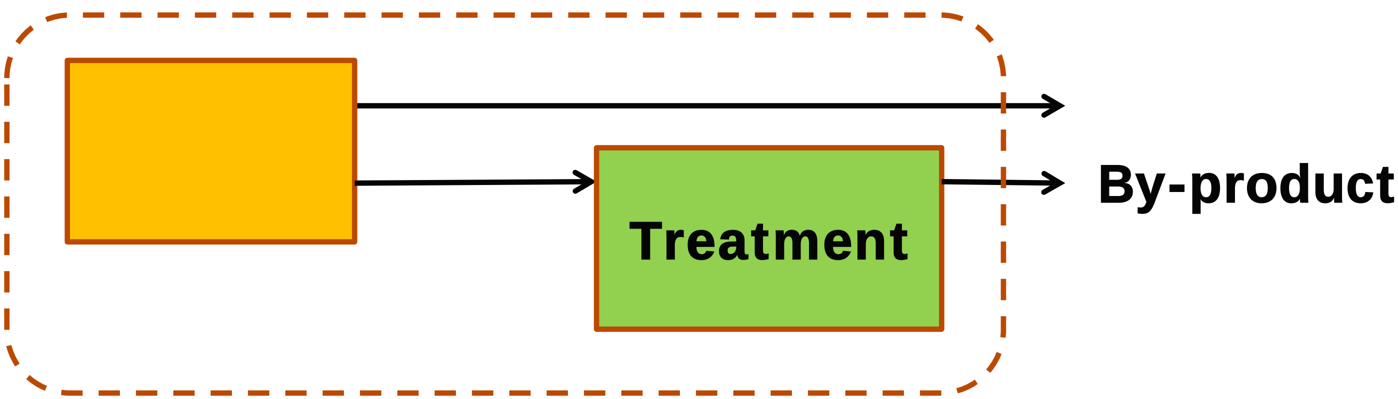
- Attributional models are often presented as having very low uncertainty, because only the precision is measured, while the accuracy (methodological bias) is ignored.
- True uncertainty (accuracy) of an attributional model can only be determined by comparing it with its consequential counterpart.
- When compared on combined precision and accuracy → clear advantage of consequential models due to their larger accuracy.

# Mythbusting

- “attributional models are closer to current reality”
- “consequential models requires more data”
- “consequential models are more costly”
- “consequential models are more uncertain”

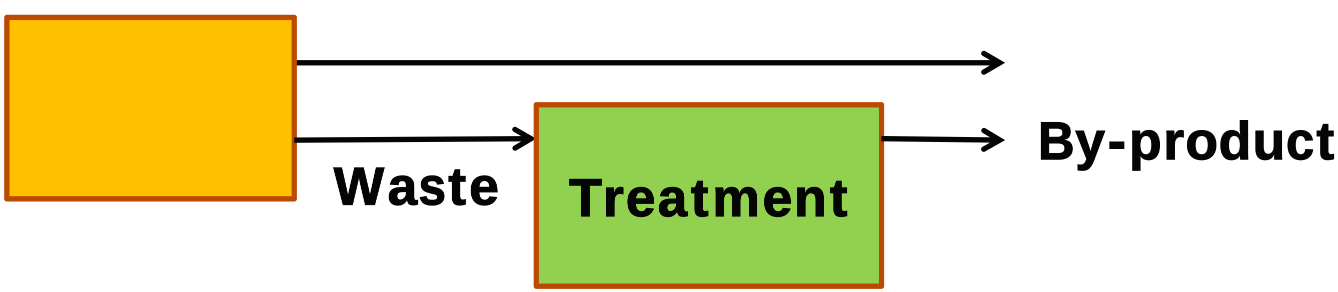
# The fallacy of simplicity: The real complexity of allocation

- Physical or economical allocation?
- What is to be allocated to?
  - Wastes vs. by-products: Economics sneeks into all allocation
- How to obtain prices in-firm?
  - Production costs: cannot be related to individual co-products
  - Opportunity costs: would turn many wastes into by-products



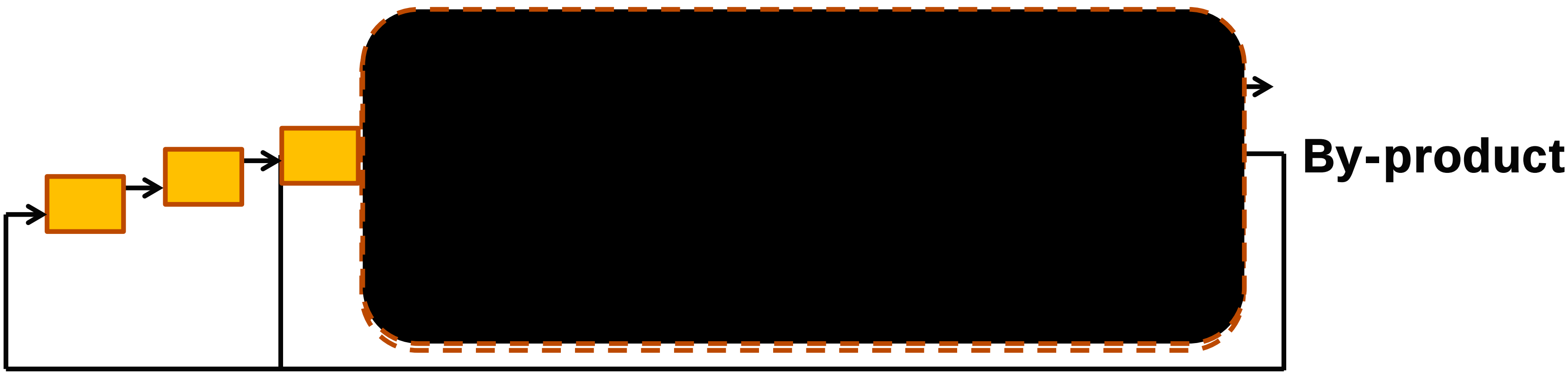
# The fallacy of simplicity:
# The real complexity of allocation

- Fluctuating prices (time, geography)
- Currency conversion
- Taxes and subsidies
- Non-market products
- Value correction
- Recycling
  - What is not recycling? Special rules for recycling?



# The fallacy of simplicity: The real complexity of allocation

- End-of-life; Closed loop; 0/100 output vs. recycled content; 100/0 input
- Closed-loop/open-loop
  - On closer inspection, all loops are closed
  - All by-products are recycled (in a closed loop)
- The point of allocation

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# Co-production according to the ILCD handbook

4 situations:

- A ("small", i.e. short-term decisions, without effects on capital investment): Use substitution with average supply, excluding by-products
- B ("big", i.e. long-term decisions, with effects on capital investment): Use substitution with constrained markets and technologies (consequential modelling)
- C1 ("accounting studies with interaction"): As A
- C2 ("accounting studies without interaction with other systems"): Use allocation hierarchy:
  - 1) Elemental composition
  - 2) Enthalpy
  - 3) QFD = true value
  - 4) Economic value

# Reproducibility: Unambiguity of the consequential modelling algorithms

- Procedures are explicit, theoretically founded, and empirically justifiable
- Data (on market boundaries, obligatory properties, market trends, production costs, constraints) can be empirically observed and any assumptions justified

# Scale of change:
# Small changes with large effects

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# Time horizon:
# Short and long term marginal technologies

- Short-term: Changes in capacity utilization only
- Long-term: Capacity changes
- Short-term decisions have both:
  - short-term consequences
  - long-term consequences (on investments)
- Long-term consequences last longer and dominate the overall impacts of a decision
- Long-term marginal technologies are more stable than the average

# Communicating LCI models

- Consequential models only include those activities that change as a result of a decision → Not always the activities that one would intuitively think → May appear counter-intuitive – until context is communicated and the model is investigated more in detail
- Attributional models may appear easy to understand at first glance, because they follow a more static logic. Communication difficulties appear only at closer examination:
  - Subjective choices of allocation factors
  - Artificial nature of allocated processes that have no real-life parallel
  - Lack of mass and energy balances for the allocated systems (violation of the law of conservation of mass and energy)
- Which communication difficulty is the largest:
  - Normative choices and artificial nature of an attributional model?
  - Initial counter-intuitive appearance of a fully explainable model?