Application of a costing model consistent with LCA to the production of pasta in a small-sized firm

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Background and motivation:

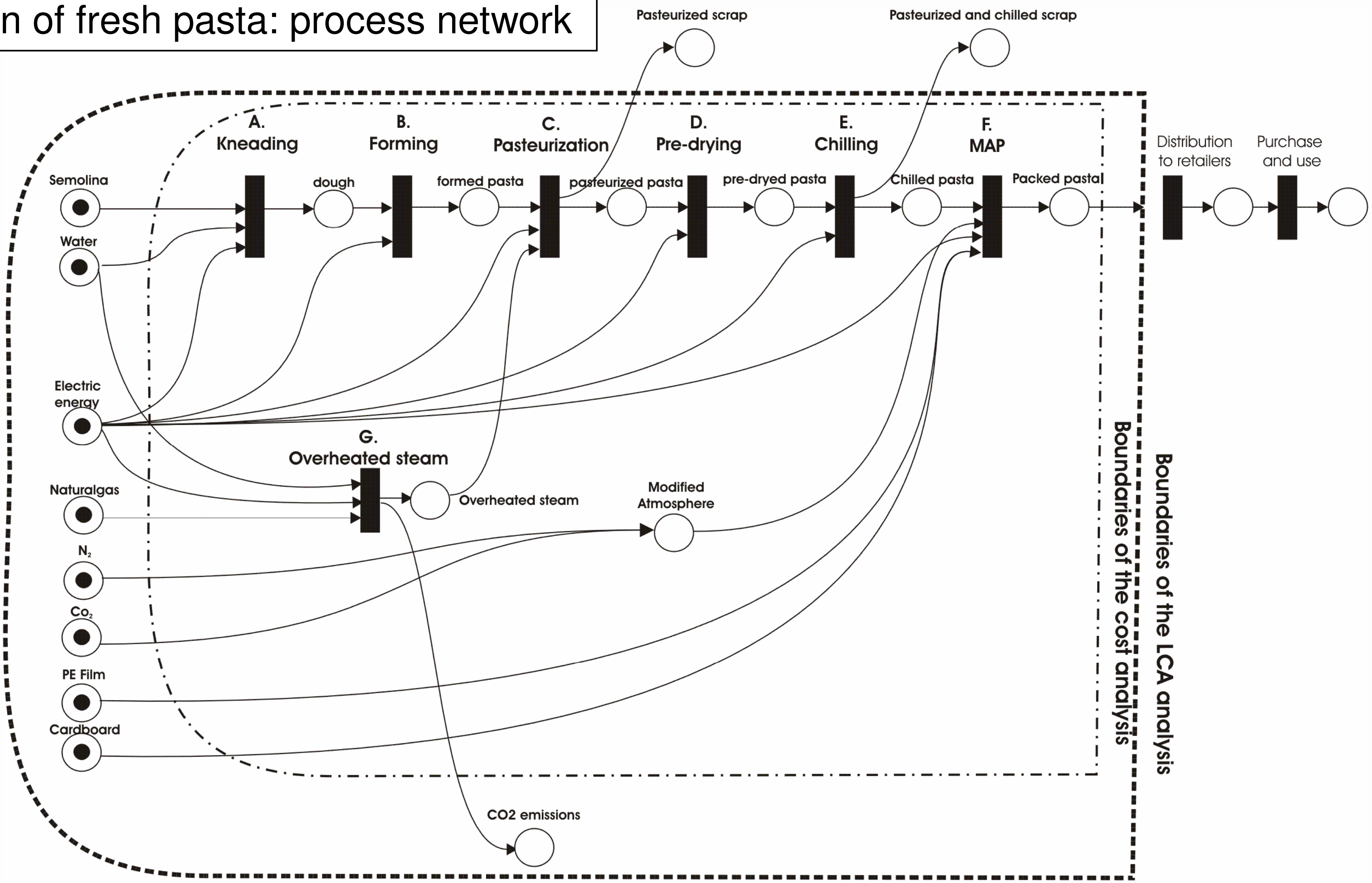
- Relevance of costing models in sustainability analysis;
  - Strong complementary relationship between environmental awareness and operational effectiveness is likely to exist (Newman and Hannah, 1996).
- Applications to food products (nondurable goods) show peculiar implementation and methodological problems:
  - Few applications of LCC to food products and, more generally, to nondurable products;
  - Mostly, investments in some new food production plant;
  - System boundaries and linkages with the life cycle inventory of the food product unclear/inconsistent;
  - Major need to explore the implications of "consistency" of costing with LCA from a computational perspective.

Objective and scope:

- To show, by means of an illustrative case study how to:
  - Model in details the food operations chain actually controlled by one relevant actor (the producer of fresh pasta), by using IOA principles;
  - Perform practical non-deterministc analysis;
  - Integrate the results obtained within an LCI dataset
- Application context: to support
  - The integrated **control and management** of physical flows and costs within a multiproduct, multistage production system that
    - Already exists and operate,
    - Produces non-durable products (e.g. food products);
  - The supply of site-specific information for a LCI.

- Which perspective is the relevant one?
  - producer, user, supply chain, society, market, or the whole physical life-cycle
- Which economic measure to include: costs or cash flows?
- Which environmental costs?
  - External; Internal material flow-related.
- Which approaches should be adopted to include economic aspects?
  - Toolbox (combination); extension (integration); hybrid models
- Which focus?
  - Data gathering; computational mechanisms
- Type of data
  - Site dependent; site specific; Inclusion of time (dynamics)

Production of fresh pasta: process network



Processes (material flows not balanced - ref.: one process run)

	unit	A(1)	A(2)	B(1)	B(2)	B(3)	C(1)	C(2)	C(3)	D(1)	D(2)	D(3)	E(1)	E(2)	E(3)	F(1)	F(2)	F(3)	G	Cost Coeffi-cients (€/unit)
		A		B			C			D			E			F			G	
Dough type 1	kg																			
Dough type 2	kg																			
Formed pasta type 1	kg																			
Formed pasta type 2	kg																			
Formed pasta type 3	kg																			
Pasteurized pasta type 1	kg																			
Pasteurized pasta type 2	kg									$\mathbf{Z}_{I,I}$										
Pasteurized pasta type 3	kg																			
Pre-dried pasta type 1	kg																			
Pre-dried pasta type 2	kg																			$\mathbf{p}$
Pre-dried pasta type 3	kg																			
Cooled pasta type 1	kg																			
Cooled pasta type 2	kg																			
Cooled pasta type 3	kg																			
Packaged pasta type 1	kg																			
Packaged pasta type 2	kg																			
Packaged pasta type 3	kg																			
Overheated steam	kg																			
Semolina type 1	kg																			
Semolina type 2	kg																			
Water (var.)	L																			
Electric energy (var.)	kWh																			
Nitrogen	L																			
Carbon dioxide	L																			
PE film	cm									$-\mathbf{M}_{\bullet,I}$										
Cardboard	pieces																			
Lead time A	min																			
Lead time B	min																			$\mathbf{p}_M$
Lead time C	min																			
Lead time D	min																			
Lead time E	min																			
Lead time F	min																			
Lead time G	min																			
Crude scrap stage C	kg																			
Crude scrap stage E	kg									$\overline{\mathbf{N}}_{I,I}$										
Moisture losses	kg																			
Returned final items	kg																			

Fixed cost overheads (ref.: one shift)

Electric energy (fix.)	kWh		
Natural Gas	MJ	$\mathbf{F}$	
Water (incl. line cln.)	m^3		$\mathbf{p}_F$
Labour (incl. setups)	min		
Fixed emissions CO_2	kg	$\mathbf{R}_{\bullet,I}$	

1 Set and exogenous production plan

(vector of
final deliveries)

Production Pogram (1 shift)

	unit	*Final deliveries*
Dough type 1	kg	y_I
Dough type 2	kg	
Formed pasta type 1	kg	
Formed pasta type 2	kg	
Formed pasta type 3	kg	
Pasteurized pasta type 1	kg	
Pasteurized pasta type 2	kg	
Pasteurized pasta type 3	kg	
Pre-dried pasta type 1	kg	
Pre-dried pasta type 2	kg	
Pre-dried pasta type 3	kg	
Cooled pasta type 1	kg	
Cooled pasta type 2	kg	
Cooled pasta type 3	kg	
Packaged pasta type 1	kg	
Packaged pasta type 2	kg	
Packaged pasta type 3	kg	
Overheated steam	kg	

2 Determine the activity levels of processes

$$\mathbf{Z}_{I,I} \cdot \mathbf{s}_I = \mathbf{y}_I \rightarrow \mathbf{s}_I = \mathbf{Z}_{I,I}^{-1} \cdot \mathbf{y}_I$$

3 Obtain a balance of material flows

$$\tilde{\mathbf{B}}_{\bullet,I} = \begin{bmatrix} -\mathbf{M}_{\bullet,I} \\ \overline{\mathbf{N}_{I,I}} \end{bmatrix} \cdot \hat{\mathbf{s}}_I \qquad \tilde{\mathbf{Z}}_{I,I} = \mathbf{Z}_{I,I} \cdot \hat{\mathbf{s}}_I$$

4 Calculate the direct costs of each process

$$\boldsymbol{\omega} = \begin{bmatrix} \mathbf{p}_M^T & \mathbf{p}_F^T \end{bmatrix} \cdot \begin{bmatrix} \tilde{\mathbf{B}}_{\bullet,I} \\ \mathbf{F} \\ \mathbf{R}_{\bullet,I} \end{bmatrix}$$

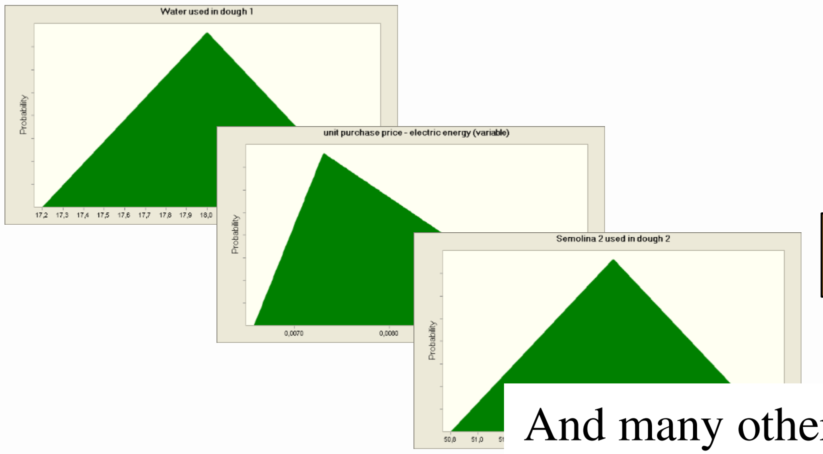
5 Calculate the unit cost of each intermediate and final product

$$\mathbf{p} = \boldsymbol{\omega} \cdot \tilde{\mathbf{Z}}^{-1}$$

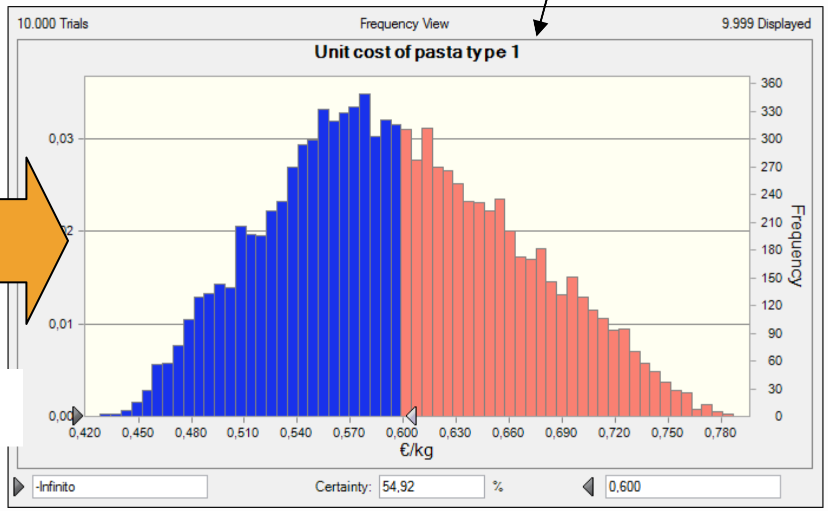
Production costs (relative to the production plan)

	A(1)	A(2)	B(1)	B(2)	B(3)	C(1)	C(2)	C(3)	D(1)	D(2)	D(3)	E(1)	E(2)	E(3)	F(1)	F(2)	F(3)	G
Direct process costs (€)	290.65	122.95	28.20	8.33	7.00	10.44	3.06	2.88	9.62	2.82	2.66	10.35	3.03	2.85	96.44	22.44	23.52	6.54
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}
	Dough type 1	Dough type 2	Formed pasta type 1	Formed pasta type 2	Formed pasta type 3	Pasteurized pasta type 1	Pasteurized pasta type 2	Pasteurized pasta type 3	Pre-dried pasta type 1	Pre-dried pasta type 2	Pre-dried pasta type 3	Cooled pasta type 1	Cooled pasta type 2	Cooled pasta type 3	Packaged pasta type 1	Packaged pasta type 2	Packaged pasta type 3	Overhead steam
Unit product costs (€/kg)	0.34	0.29	0.38	0.33	0.32	0.39	0.35	0.34	0.42	0.38	0.37	0.43	0.39	0.38	0.56	0.51	0.507	0.05

6 Associate uncertainty to the parameters and run Monte Carlo Simulation



And many others…



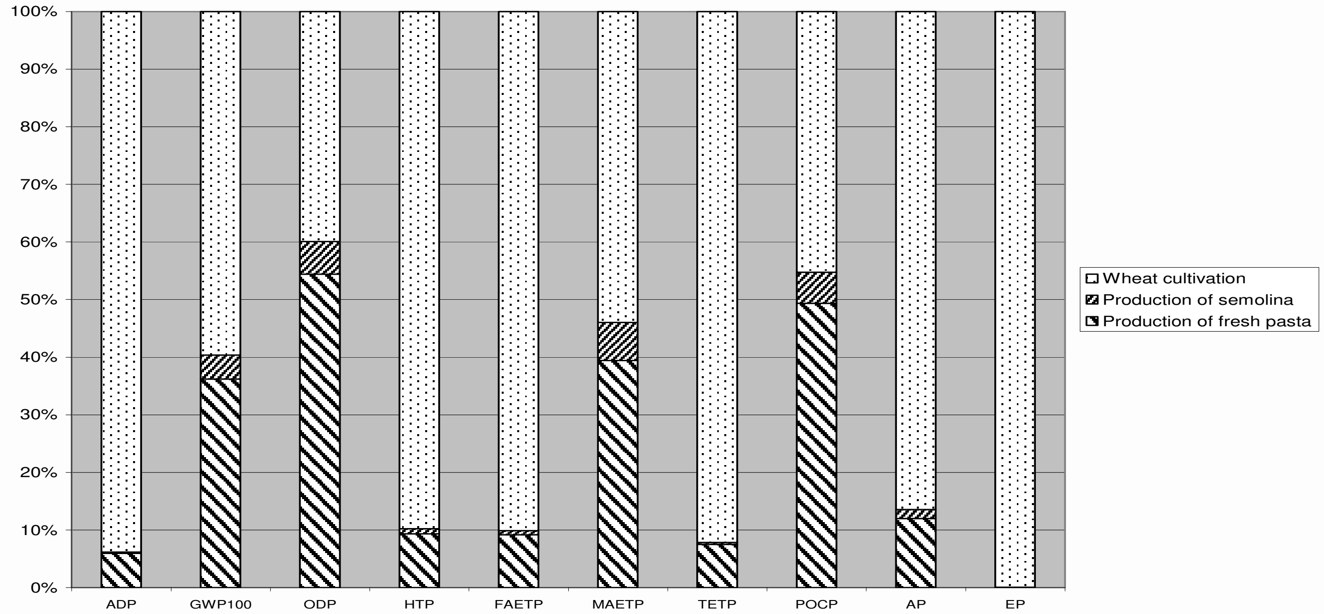
Turning the costing model (multi-product) into LCA:

- Re-define the vector of final deliveries $\mathbf{y}_{LCA\_process}$ such as:
    - It shows just one positive entry (the amount of output of one chosen product type)
- Solve: $\tilde{\mathbf{Z}}_{I,I} \cdot \mathbf{s}_{LCA\_process} = \mathbf{y}_{LCA\_process}$
- Obtain the unit process for use in LCA as a column vector:

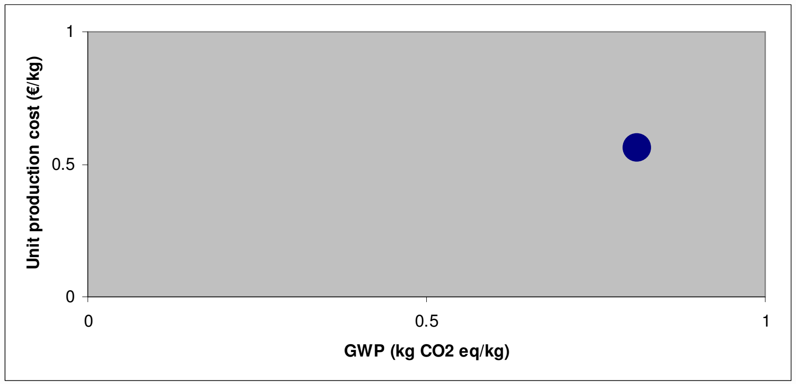
$$\begin{bmatrix} \tilde{\mathbf{Z}}_{\bullet,I} \\ \tilde{\mathbf{B}}_{\bullet,I} \\ \mathbf{F} \\ --- \\ \mathbf{R}_{\bullet,I} \end{bmatrix} \cdot \mathbf{s}_{LCA\_process} = \begin{bmatrix} \mathbf{a} \\ - \\ \mathbf{b} \end{bmatrix}$$

- Link properly the new unit process within a process network database to form a LCI
- Run LCA

Example of contribution analysis (Ref: 1kg of fresh pasta “type 2”) by using CMLCA 5.1 and Ecoinvent Database



Example of combination of cost and environmental coordinates (Ref: 1kg of fresh pasta “type 2”)



Additional steps: process inefficiencies (scraps/by-products) and **allocation**

Entries of C(2) multiplied by λ=0.998 and (1-λ) respectively

Variable cost drivers	unit	C(2)	C(SCRAP)	E(2)	E(SCRAP)	F(2)	F(SCRAP)	H
Dough type 1	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Dough type 2	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Formed pasta type 1	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	-7.79688	-0.00312	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	7.79688	0.0	0.0	0.0	0.0	0.0	
…sta type 2	kg	0.0	0.00312	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	-40.649	-0.0407	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	0.0	0.0	0.0	0.0	
	kg	0.0	0.0	40.6493	0.0	-4.9979	-0.1041	
SCRAP Cooled pasta type 2		0.0	0.0	0.0	0.0407	-0.0050	0.0	
Cooled pasta type 3	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Packaged pasta type 1	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Packaged pasta type 2	kg	0.0	0.0	0.0	0.0	5.0000	0	
SCRAP Packaged pasta type 2	kg	0.0	0.0	0.0	0.0	0.0	0.1020	
Packaged pasta type 3	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Overheated steam	kg	-0.78759	-0.00032	0.0	0.0	0.0	0.0	
DEMAND OF WASTE COLLECT.	kg							
Semolina type 1	kg	0.0	0.0		0.0	0.0	0.0	
Semolina type 2	kg	0.0	0.0		0.0	0.0	0.0	
Water (var.)	L	0.0	0.0	0.0	0.0	0.0	0.0	
Electric energy (var.)	kWh	0.0	0.0	0.0	0.0	-0.0416	-0.0009	
Nitrogen	L	0.0	0.0	0.0	0.0	-22.4327	-0.4673	
Carbon dioxide	L	0.0	0.0	0.0	0.0	-7.4449	-0.1551	
PE film	cm	0.0	0.0	0.0	0.0	-181.2245	-3.7755	
Cardboard	pieces	0.0	0.0	0.0	0.0	-0.9796	-0.0204	
Lead time A	min	0.0	0.0	0.0	0.0	0.0	0.0	
Lead time B	min	0.0	0.0	0.0	0.0	0.0	0.0	
Lead time C	min	-2.99880	-0.00120	0.0	0.0	0.0	0.0	
Lead time D	min	0.0	0.0	0.0	0.0	0.0	0.0	
Lead time E	min	0.0	0.0	-15.984	-0.0160	0.0	0.0	
Lead time F	min	0.0	0.0	0.0	0.0	-0.9796	-0.0204	
Lead time G	min	0.0	0.0	0.0	0.0	0.0	0.0	
Waste collection cost (batch of 50kg)	€	0.0	0.0	0.0	0.0	0.0	0.0	
Crude scrap stage C	kg	0.0	0.00312	0.0	0.0	0.0	0.0	
Crude scrap stage E	kg	0.0	0.0	0.0	0.0407	0.0	0.0	
Moisture losses	kg	0.0	0.0	0.0	0.0	0.0	0.0	
Returned final items	kg	0.0	0.0	0.0	0.0	0.0000	0.1020	
Fixed cost drivers								
Electric energy (fix.)	kWh	-6.201976	-0.002483	-7.2533	-0.007268	-7.094888	-0.14781	0.0
Natural Gas	MJ	0	0	0	0	0	0	0.0
Water (incl. line cln.)	m^3	-49.97999	-0.020008	-49.949	-0.05005	0	0	0.0
Labour (incl. setups)	min	0	0	0	0	-19.59184	-0.408163	0.0
Fixed emissions CO_2	kg	0	0	0	0	0	0	0.0

$\mathbf{Z}_{I,II}$

$\mathbf{Z}_{II,I}$

$\mathbf{Z}_{II,II}$

$\mathbf{B}_{\bullet,II}$

Calculate the recycling percentages (for n_I production processes and k waste types)

in this case study: null vector

$$\forall k, (\rho_I)_k = \sum_{j=1}^{n_I} (\underline{\mathbf{N}}_{I,I})_{kj} \times (\mathbf{s}_I)_j$$

$$\forall k, (\eta_I)_k = \sum_{j=1}^{n_I} (\overline{\mathbf{N}}_{I,I})_{kj} \times (\mathbf{s}_I)_j$$

$$r_k = \frac{(\eta_I)_k}{(\rho_I)_k} \qquad \mathbf{r}_I = [r_1 \quad \cdots \quad r_k \quad \cdots]^T$$

Turn the different types of wastes/by-products into the demand of treatment processes

$$\mathbf{Q} = [q_{lk}] \quad \text{where} \quad 0 \leq q_{lk} \leq 1$$

$$\tilde{\mathbf{Z}}_{II,I} = [-\mathbf{Q} \cdot (\mathbf{I} - \hat{\mathbf{r}}_I)] \cdot (\overline{\mathbf{N}}_{I,I} \cdot \hat{\mathbf{s}}_I)$$

in this case study: waste collection only and no recycling of waste types generated by the treatment processes (simplest case)

Calculate the scaling factors again, taking into account the treatment processes

$$\mathbf{s}_{II} = \mathbf{X}^{-1} \cdot \mathbf{y}_{II} \quad \text{where} \quad \mathbf{X} = \begin{pmatrix} \tilde{\mathbf{Z}}_{I,I} & \mathbf{Z}_{I,II} \\ \tilde{\mathbf{Z}}_{II,I} & \mathbf{Z}_{II,II} \end{pmatrix}$$

$$\tilde{\mathbf{X}} = \mathbf{X} \cdot \hat{\mathbf{s}}_{II} \quad \text{and} \quad \tilde{\mathbf{B}} = (\tilde{\mathbf{B}}_{\bullet,I} \quad | \, \mathbf{B}_{\bullet,II}) \cdot \hat{\mathbf{s}}_{II}$$

Calculate the direct process costs and the unit costs again

$$\boldsymbol{\omega} = \begin{bmatrix} \mathbf{p}_M^T & \mathbf{p}_F^T \end{bmatrix} \cdot \begin{bmatrix} \tilde{\mathbf{B}} \\ \mathbf{F} \end{bmatrix} \quad \text{and} \quad \mathbf{p} = \boldsymbol{\omega} \cdot \tilde{\mathbf{X}}^{-1}$$

The cost of producing and disposing of waste (non value-added activity) is now explicit

Costs (with allocation)	unit	*C(2)*	*C(SCRAP)*	*E(2)*	*E(SCRAP)*	*F(2)*	*F(SCRAP)*	*H*
Direct process costs (€)	kg	3.058	0.002	3.027	0.003	21.94	0.45706	10.48
Unit cost of formed pasta type 2	€/kg	0.35	0.75	0.39	0.795	0.50	0.912056	0.4

Concluding remarks

- Advantages of matrix-based costing:
  - Unlike "traditional LCC" it applies to
    - Non durable good such as food products, not only durable goods;
    - Existing processes, not only to prospective investments.
  - Supports actual managerial decision making processes within the firm;
- Consistency with LCA and integration: a matter of computational structure
  - Theoretically, whatever complex multi-stage multi-product system can be analyzed in sufficient details by Input-Output accounting, and then turned into a black-box unit process for use within LCI;
  - In practice, carefully consider the extent to which it is possible or useful to gain insight into the cost structure of one or more supply chain actors;
- Profitability within the Agri-food supply chain needs careful assessment