Eco-design approaches for developping sustainable processes : New opportunities for the dairy sector

Geneviève Gésan-Guiziou

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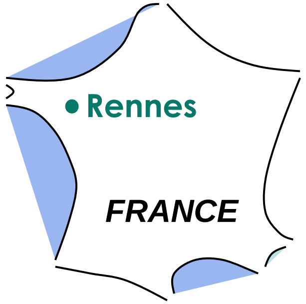


STLO   RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité   INRAE   L'INSTITUT agro Rennes Angers   CARNOT Qualiment Reseau de recherche pour l'innovation alimentaire

Definition

Technical criteria

Economic criteria

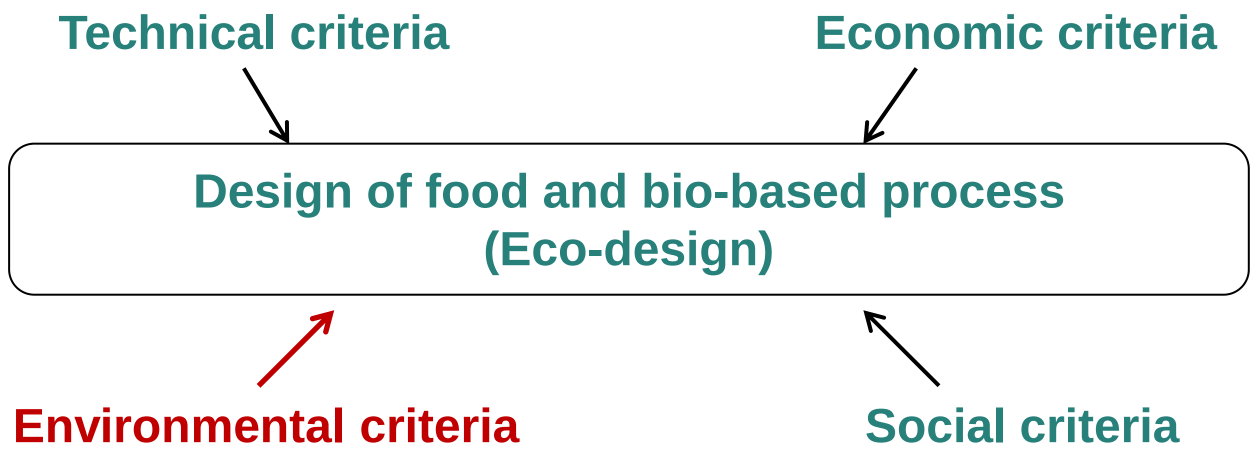
Design of food and bio-based process
(Eco-design)

Environmental criteria

Social criteria

Eco-design : Integration of “environmental impacts” from the early design or re-design stage of the process

Definition



Eco-design : Integration of "environmental impacts" from the early design or re-design stage of the process

Eco-efficiency is the equation between the value of a product/ service/process and its impact on the environment

Why eco-design food processing ?

1/ The food processes face evolving economic situation : increase in price of energy & water; depletion of water supply; increase in environmental taxes …

2/ The transformation processes use raw materials with high environmental impacts. They should avoid losses and wastes.

3/ The transformation processes should meet demands / regulations in terms of eco-designed products

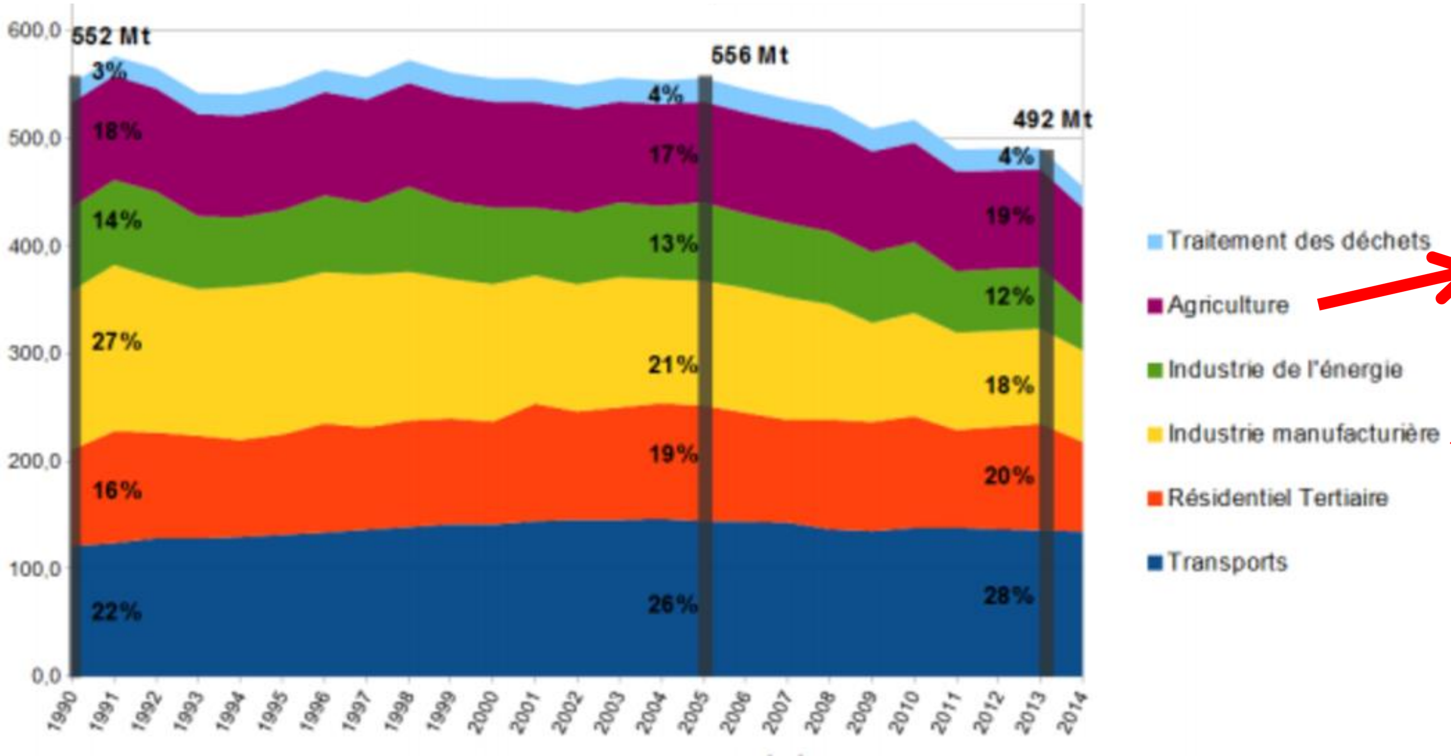
- evolving regulatory framework : e.g. Ecological labelling
- increase in consumer awareness

Encouragement by COP 21 in Paris, 7 years ago

Why eco-design food processing ?

Much effort has to be made on manufacturing industries in the next years (COP 21)

Evolution of Greenhouse gas emissions in France from 1990 and 2013

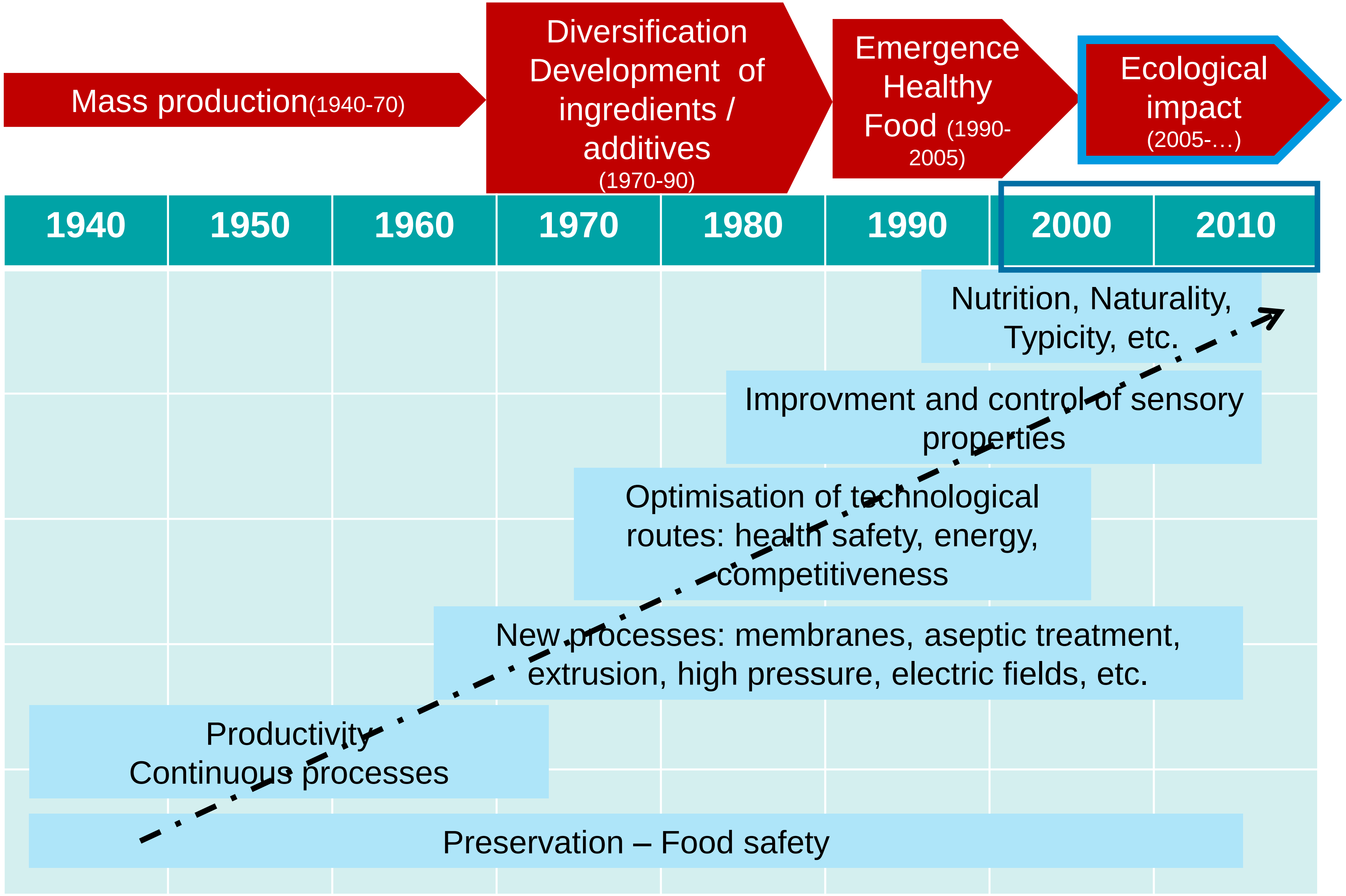


COP 21

-12 % within the next 10 years ; and -50% by 2050

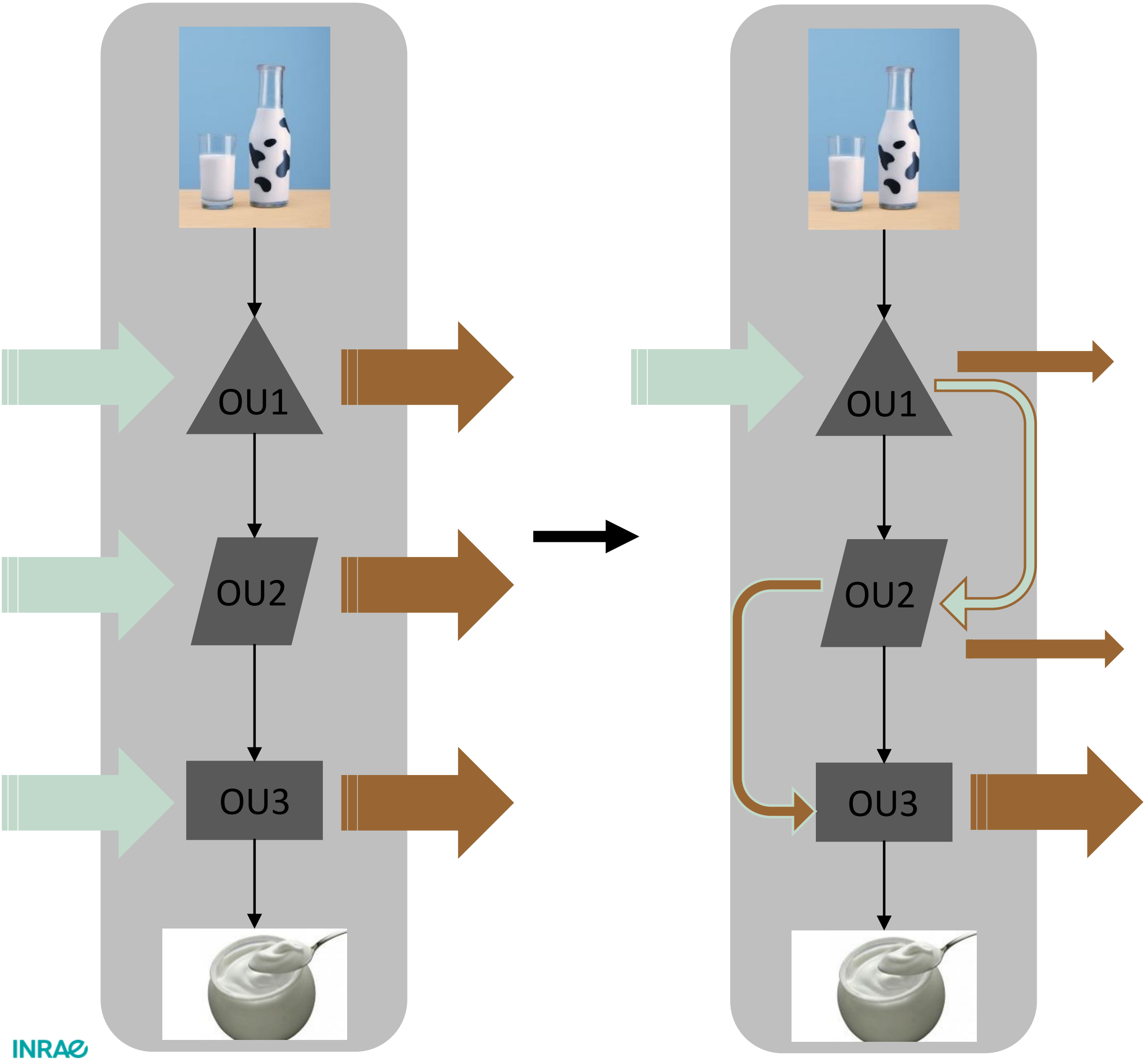
-24 % within the next 10 years ; and -75 % by 2050

Evolution in food processing



Adapted from Trystram, 2011

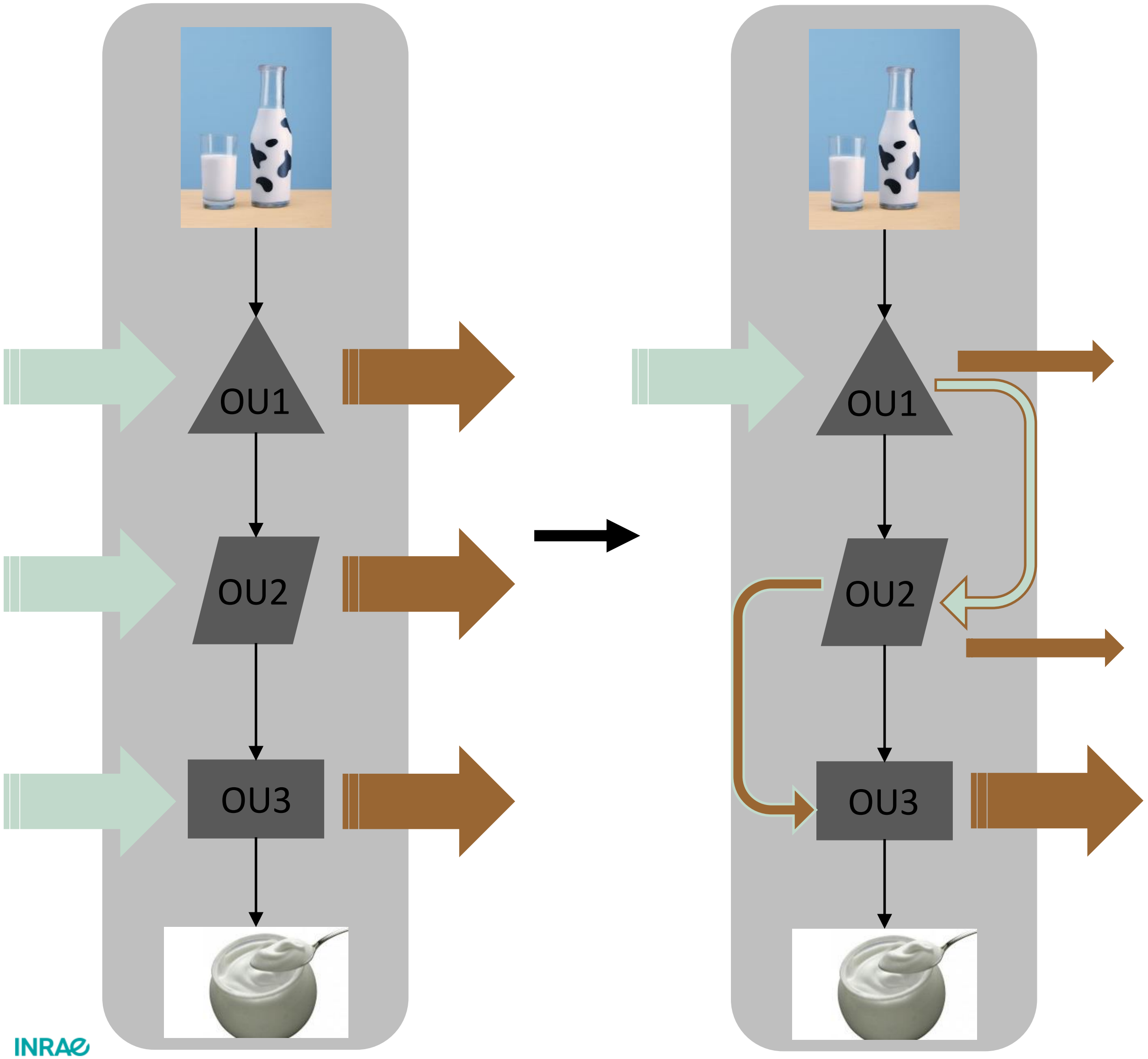
Eco-design strategy n°1: Minimization of resources



- Reuse / redistribution of the flows making use of intelligent design methods (eg: Pinch analysis)
- Modifications of operating conditions (temperature, flux < critical flux, …)

→ Reduction of costs (driver = economy)

Eco-design strategy n°1: Minimization of resources



- Reuse / redistribution of the flows making use of intelligent design methods (eg: Pinch analysis)
- Modifications of operating conditions (temperature, flux < critical flux, …)

→ Reduction of costs (driver = economy)

- Single action on water or energy consumptions
- Does not consider modifications of food product
- Does not allow search for a global optimum
- Low potential of innovation, but significant economic and environmental benefits

Eco-design strategy n°1: Minimization of resources

- Reduction of energy consumption in ripening chambers

EuropeanTruefood (2006-2010), Picque et al., IDJ, 2009

Context: The ripening cheese rooms are constantly ventilated, and the energy cost for this ventilation is high (50% of the cost linked to ripening)

1- A sequential ventilation procedure based on the control of temperature was adopted

2- Electrical energy savings =~ 50-60 % of the consumption linked to ventilation with no significant impact on the quality of the cheeses (microbiology, biochemistry)

Cellar volume ~ 1300 m^3
Ripened cheeses ~ 20 000

- Recommendations for rationalizing cleaning-in-place in dairies

Industrial project, Alvarez et al. JDS, 2010

1- A new strategy based on the on-line and off-line use of sensors and tracers was implemented (case study of an ultra-high temperature heat exchanger)

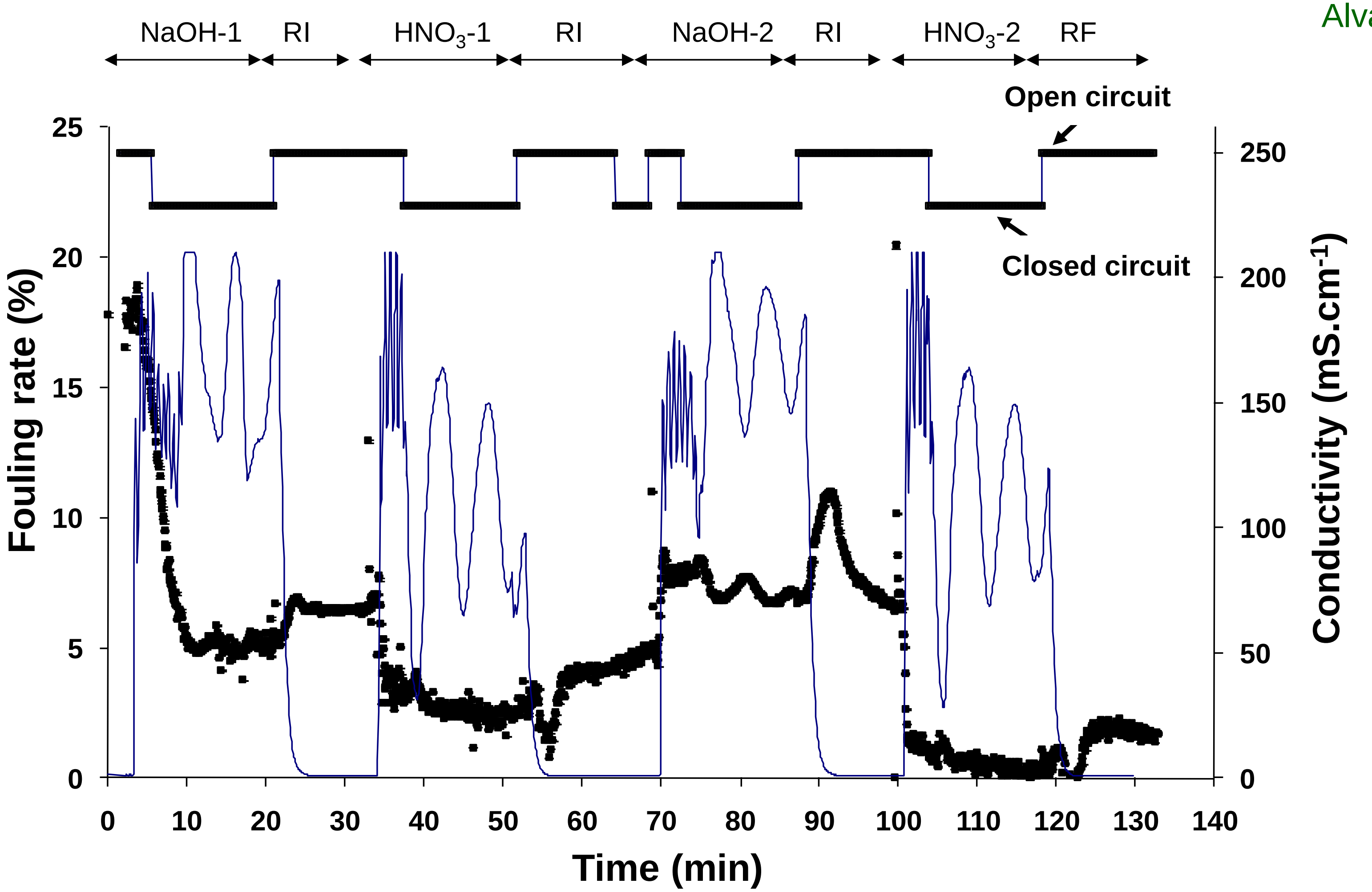
2- The CIP operating time and the volume and load of effluents was reduced by half.

Eco-design strategy n°1: Minimization of resources

Example of an ultra-high temperature heat exchanger - chocolate cream

Initial situation

Alvarez et al., JDS, 2010

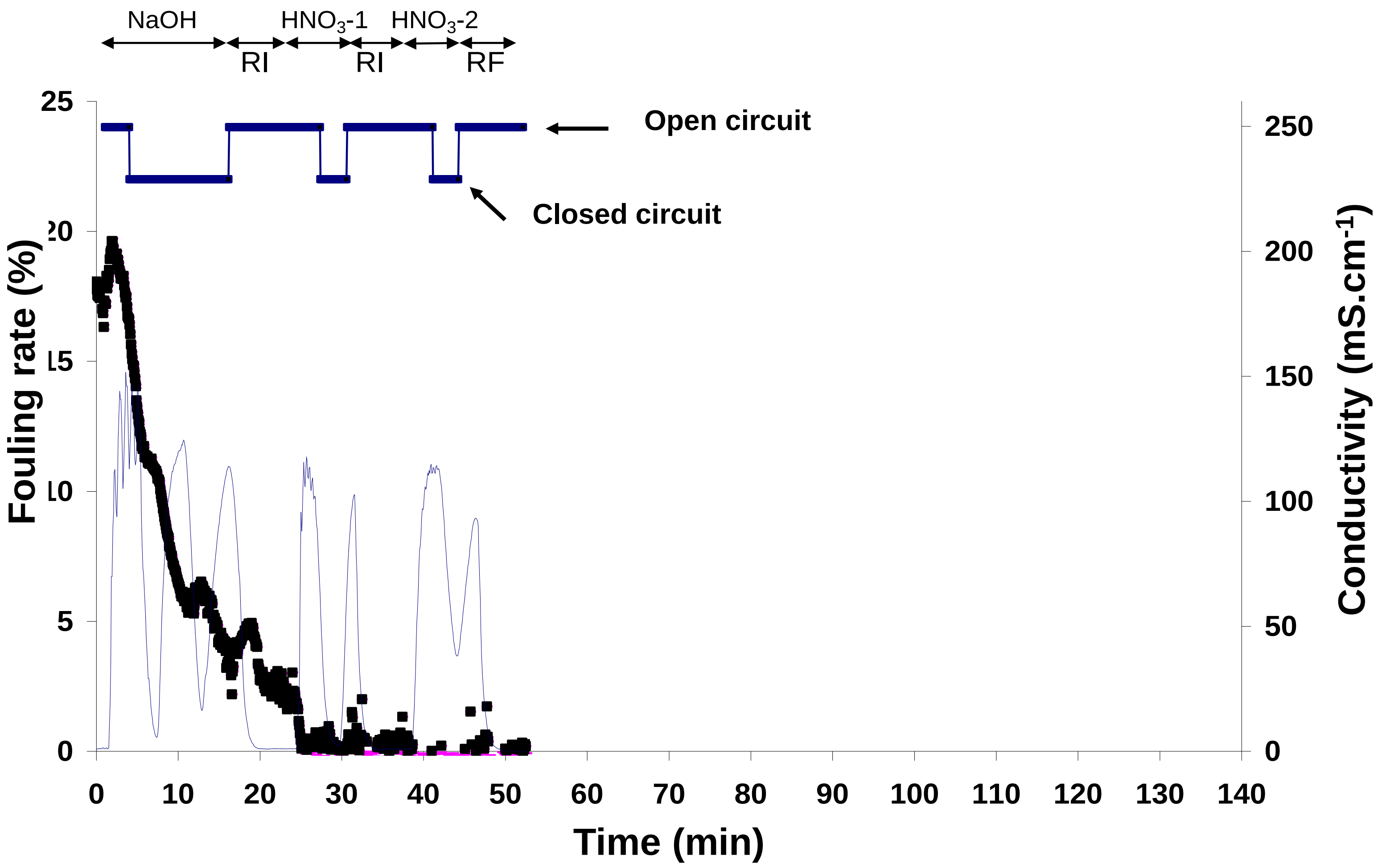


Eco-design strategy n°1: Minimization of resources

Example of an ultra-high temperature heat exchanger - chocolate cream

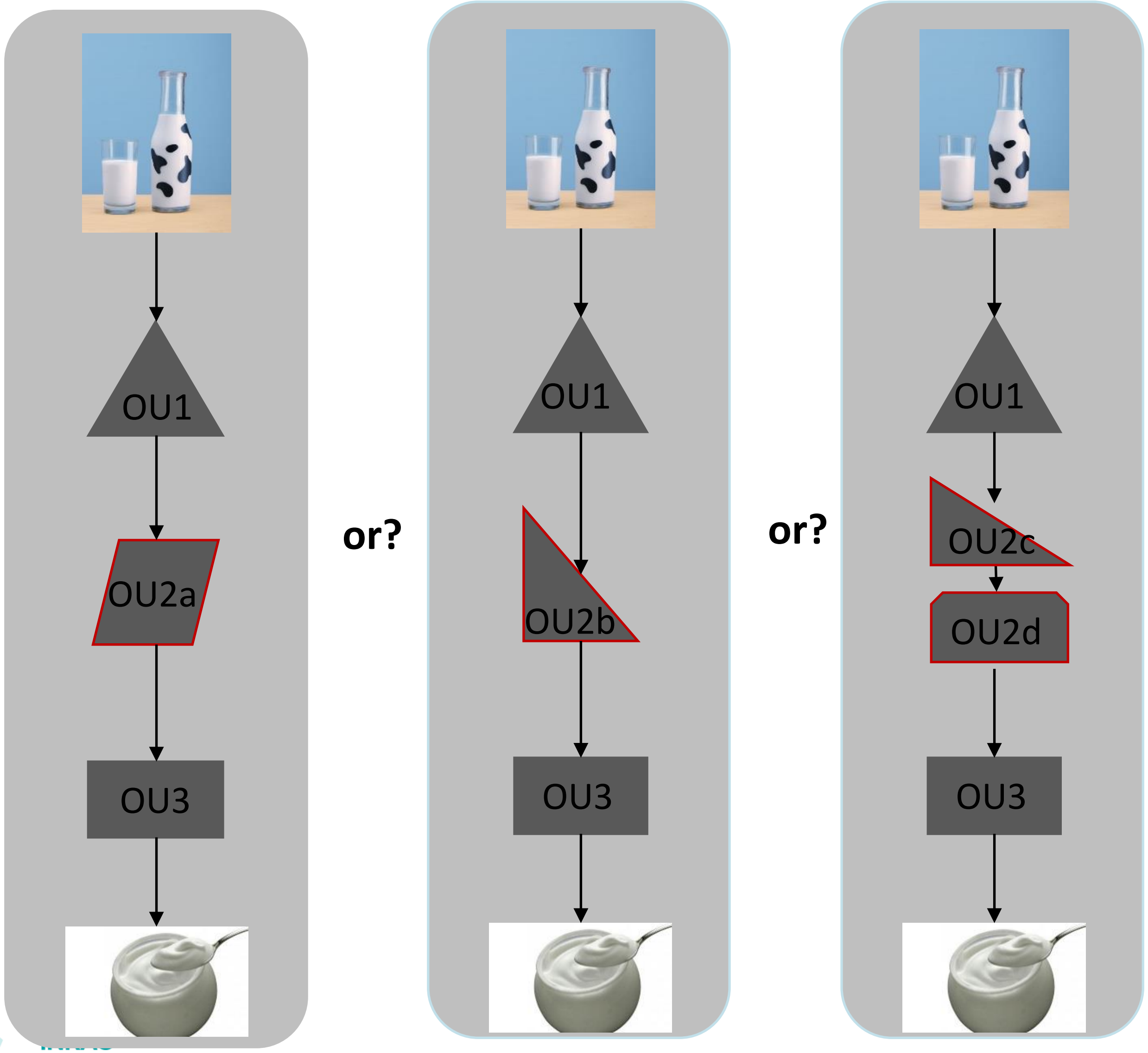
Improved situation

Alvarez et al., JDS, 2010



Eco-design strategy n°2: Comparative assessment of processes

Life Cycle Analysis, LCA

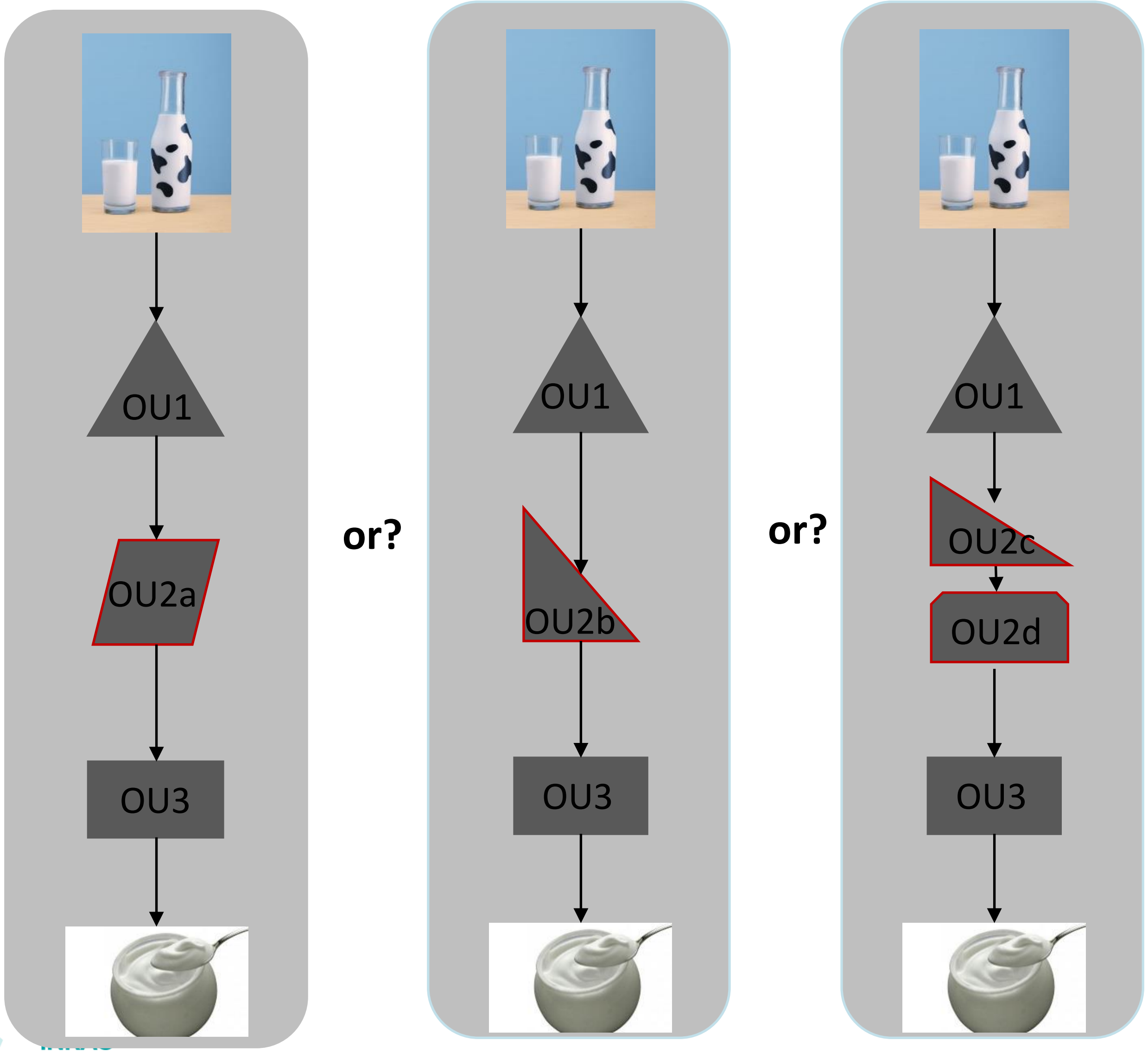


- Simple and readily applicable
- Easy when product is not affected (constant Functional Unit)
- Identification of « hot spots »
- Comparison of scenarios and technologies

OU: unit operation

Eco-design strategy n°2: Comparative assessment of processes

Life Cycle Analysis, LCA

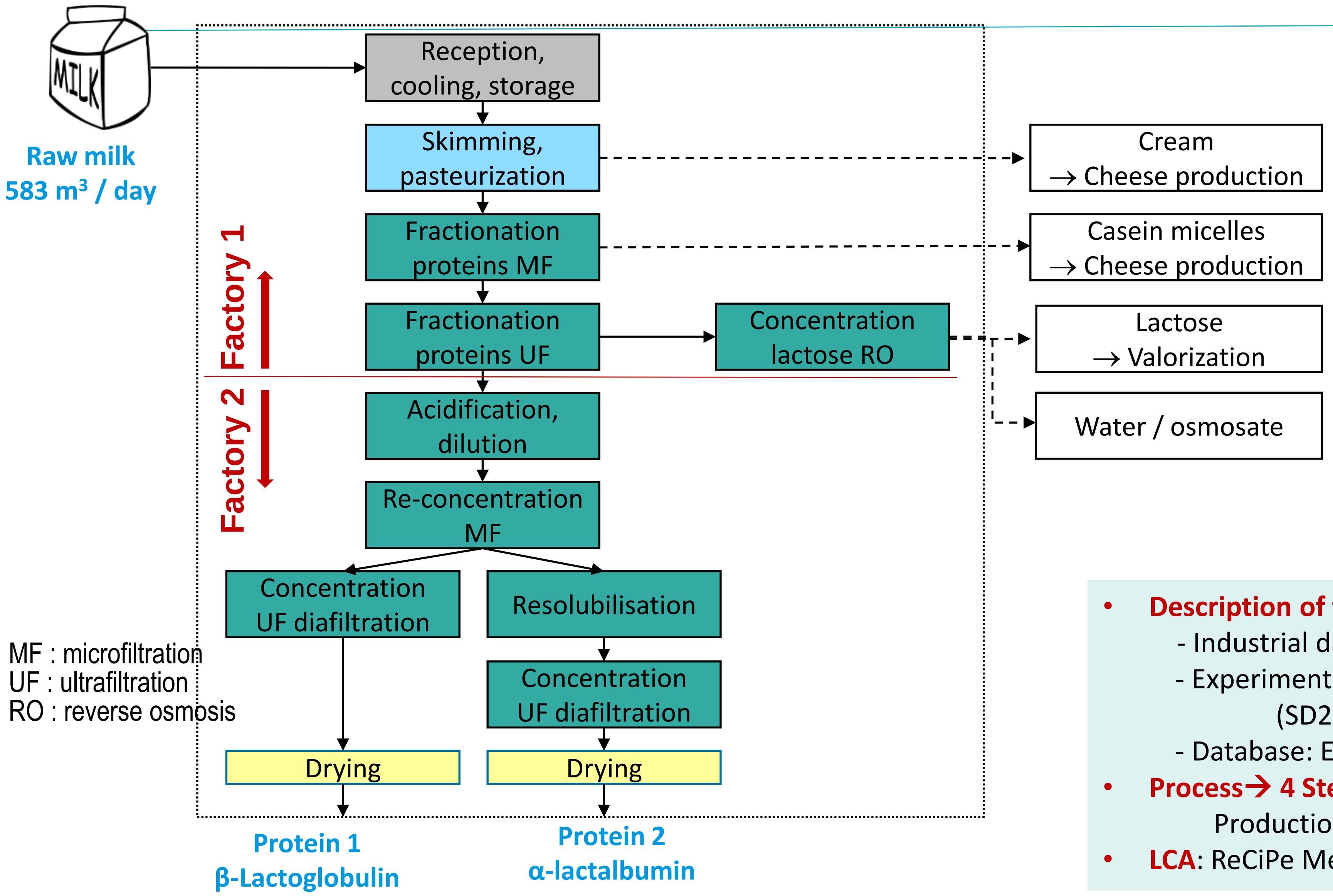


OU: unit operation

- Simple and readily applicable
- Easy when product is not affected (constant Functional Unit)
- Identification of « hot spots »
- Comparison of scenarios and technologies

- Tricky when product (and Functional Unit) is affected
- Collection of data difficult
- Does not offer solutions for improvement
- Does not allow search for a global optimum

Industrial milk protein fractionation process

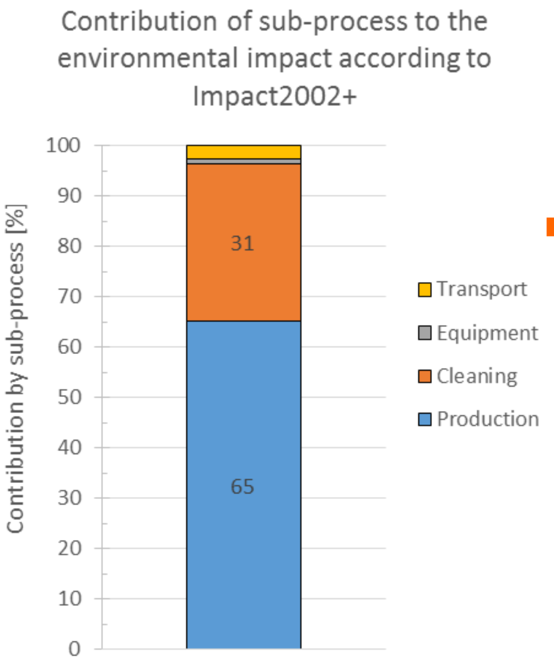


- **Description of the process steps → Data**
  - Industrial data
  - Experimental data + software – Spray drying (SD2P® software, Schuck et al. 2009)
  - Database: Ecoinvent 3.0
- **Process → 4 Steps**
  Production, cleaning, equipment, transport
- **LCA**: ReCiPe Method + SimaPro 8.0

Gésan-Guiziou et al. SPT 2019

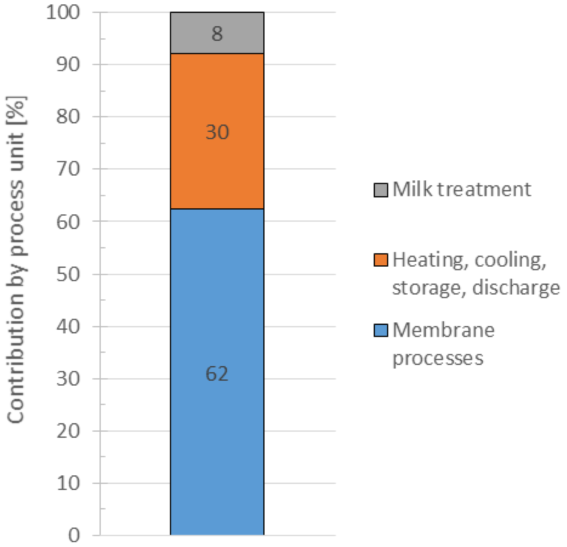
Industrial milk protein fractionation process

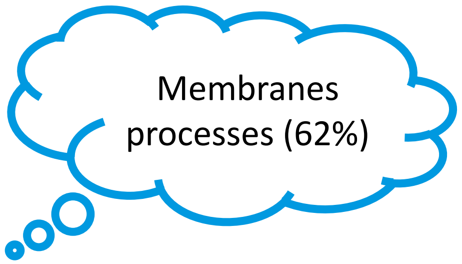
Examples of results



Production (65 %) and cleaning (31 %) phases are the main contributors to the overall environmental impact

Cleaning





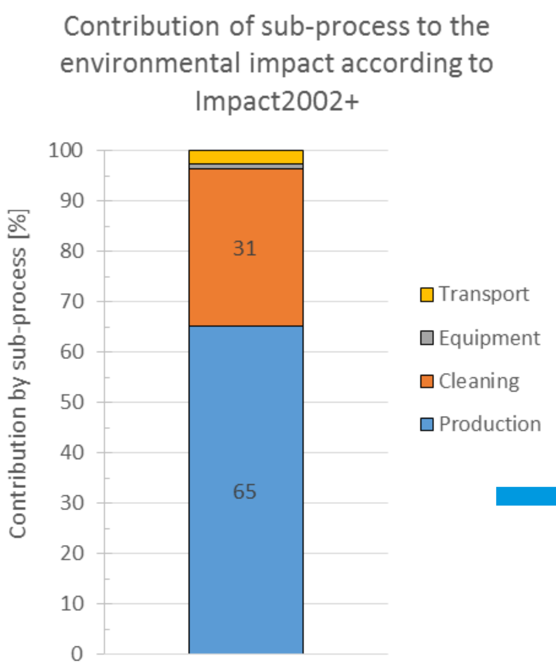
Cleaning of the membranes is the main contributor to the environmental impact of the entire cleaning phase (multiple single passage steps requiring high amounts of freshwater and detergents)

Underestimation of the impact stemming from cleaning the membranes due to missing data for certain cleaning agents that are contained in the complex cleaning solutions

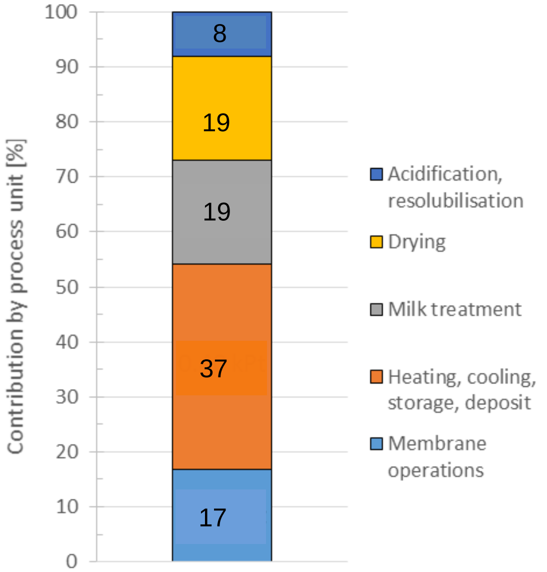
Gésan-Guiziou et al. SPT 2019

Industrial milk protein fractionation process

Examples of results



Production (65 %) and cleaning (31 %) phases are the main contributors to the overall environmental impact



Heating / cooling (≈ 37 %) and membranes processes (17%)

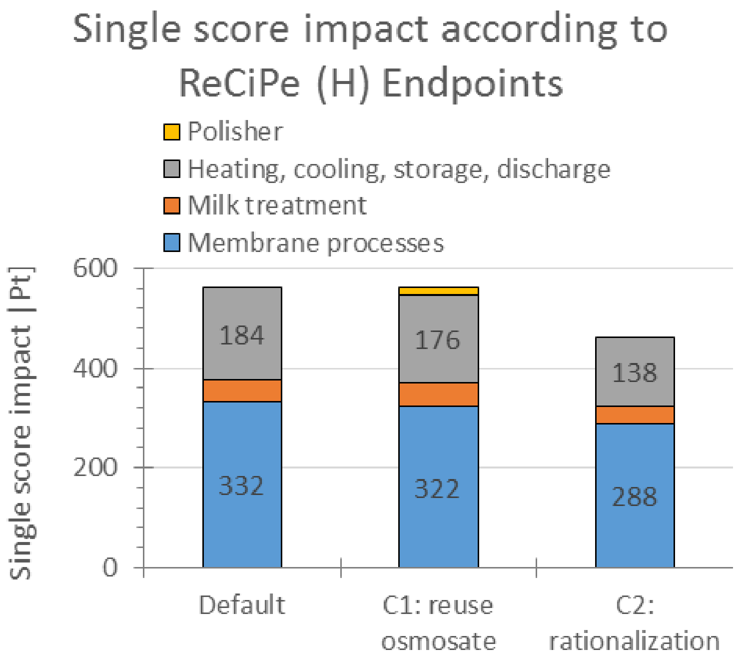
MF 0.1 µm

Membranes operations (17%) and heating / cooling / storage (37 %) operations are the main contributors to the overall environmental impact of the production phase

Gésan-Guiziou et al. SPT 2019

Industrial milk protein fractionation process
Examples of results

Impacts of 2 novel cleaning strategies / alternatives



C1: Reutilization of the water from the lactose concentration process → reduction of the freshwater consumption but requirement of a polisher

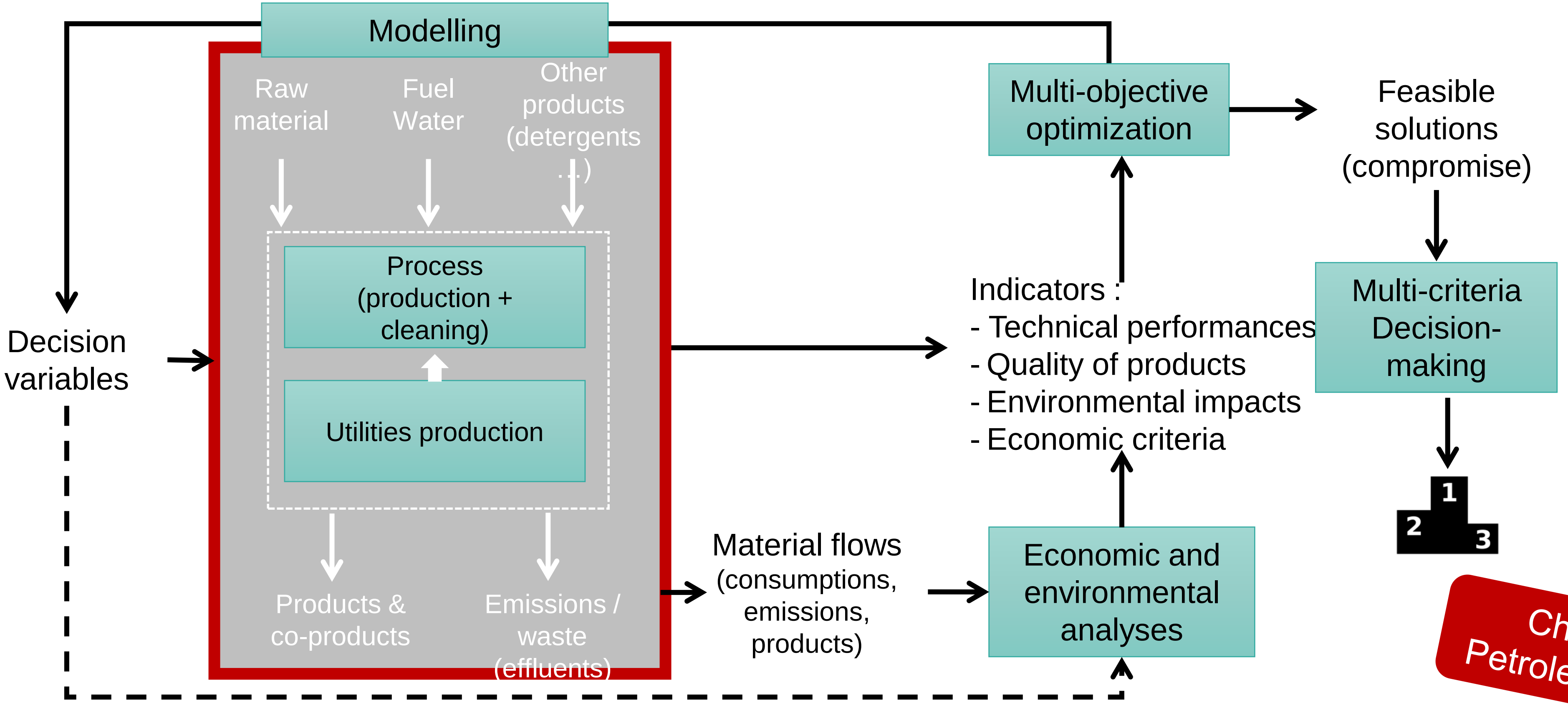
C2: Rationalization of the cleaning solutions (less frequent caustic soda CIP renewal, reduction of cleaning time, etc.) → reduced consumption of resources

If regarded in detail, the optimization strategies show an improvement for certain categories : ReCiPe: in 12/18

Gésan-Guiziou et al. SPT 2019

Eco-design strategy n°3: Multi-objective optimization

Azzaro-Pantel et al, FBP, 2022
Moulton Junior Medals 2023, awarded by IChemE



Chemical and Petroleum Industries

Simultaneous optimization of conflicting objectives

Eco-design strategy n°3: Multi-objective optimization

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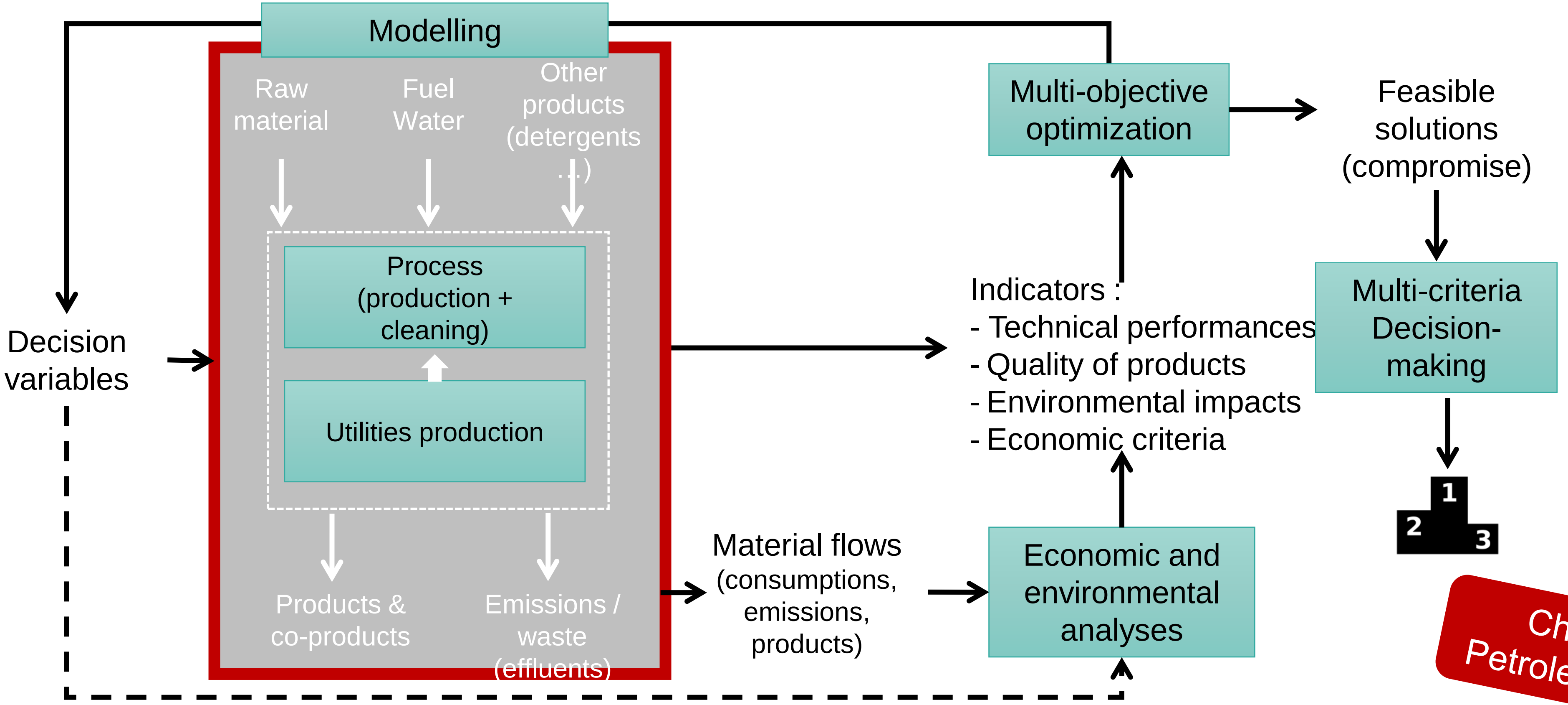


Chemical and Petroleum Industries

Simultaneous optimization of conflicting objectives

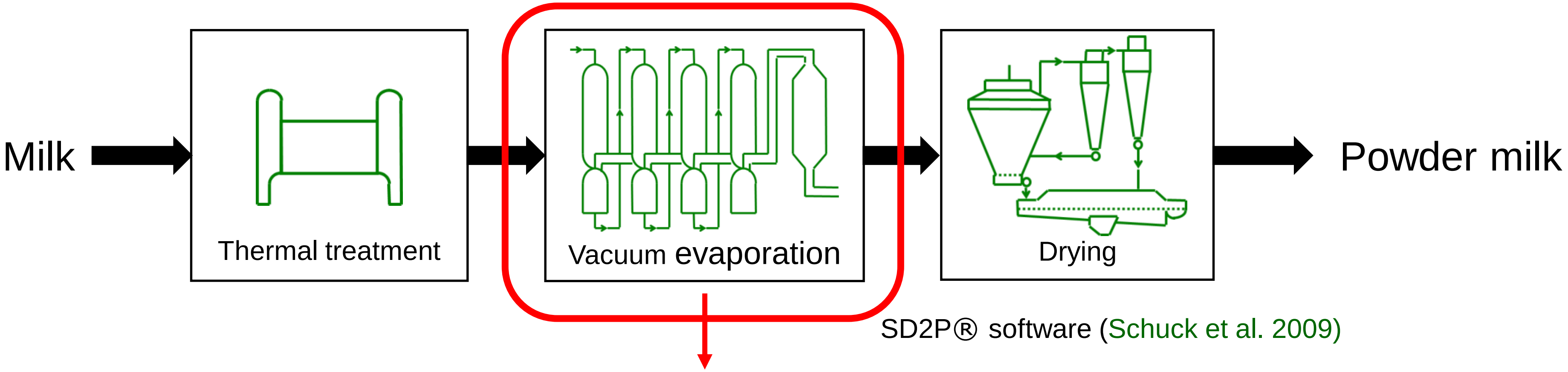
Lack of process models
- Food properties difficult to predict
- Lack of knowledge on the impact of decision variables
- Scarce use of process simulators

Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator

Concentration and drying of dairy products

- ❑ Highly energy-intensive process: 25% of the total energy used in the dairy industry (Agreste, 2011)



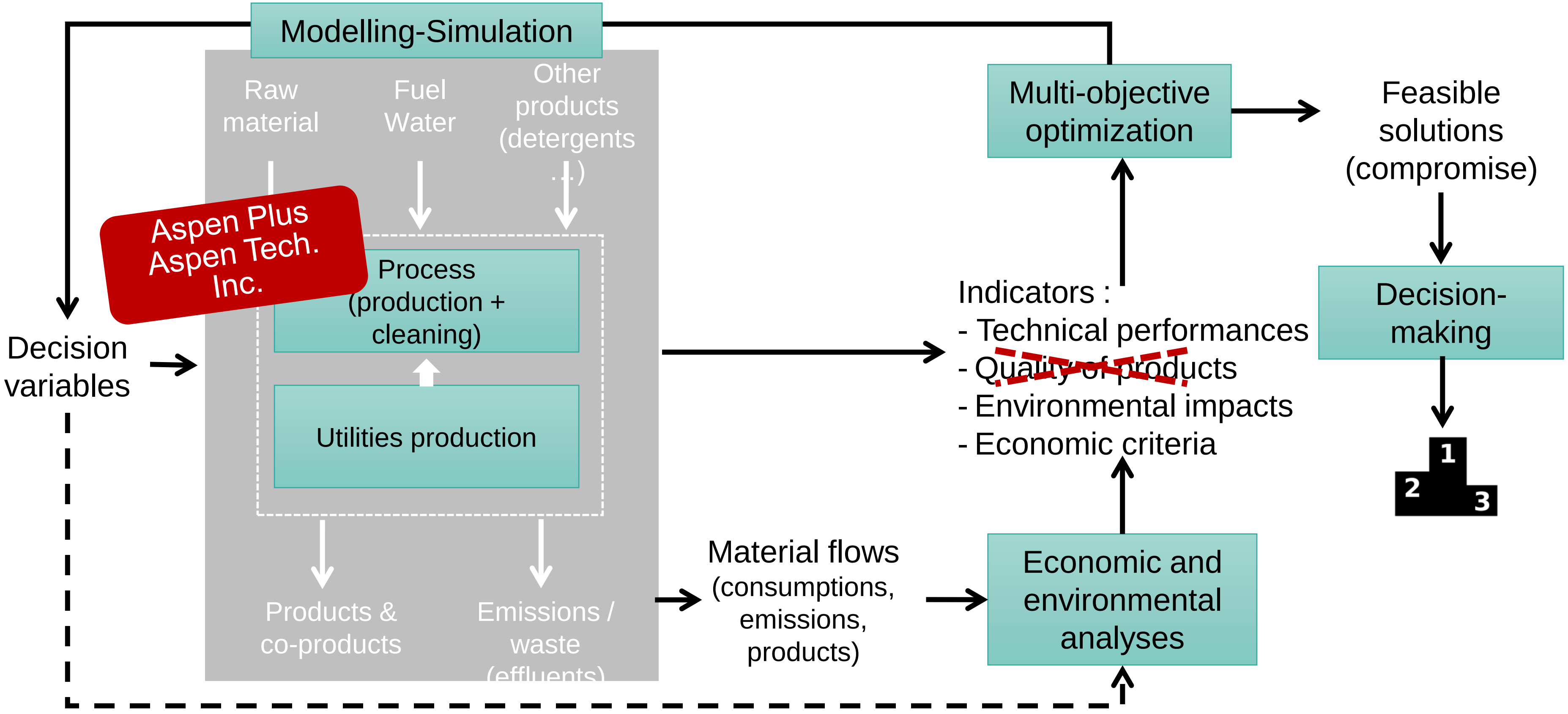
SD2P® software (Schuck et al. 2009)

- ❑ > 50% of the energy consumption of the overall concentration and drying process (Jebson, 1991)
- ❑ Various options for evaporator design

➢ **Use of a Process simulator**
  - ➢ **to design evaporator**
  - ➢ **to choose the primary source of energy needed for the steam production**

Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator



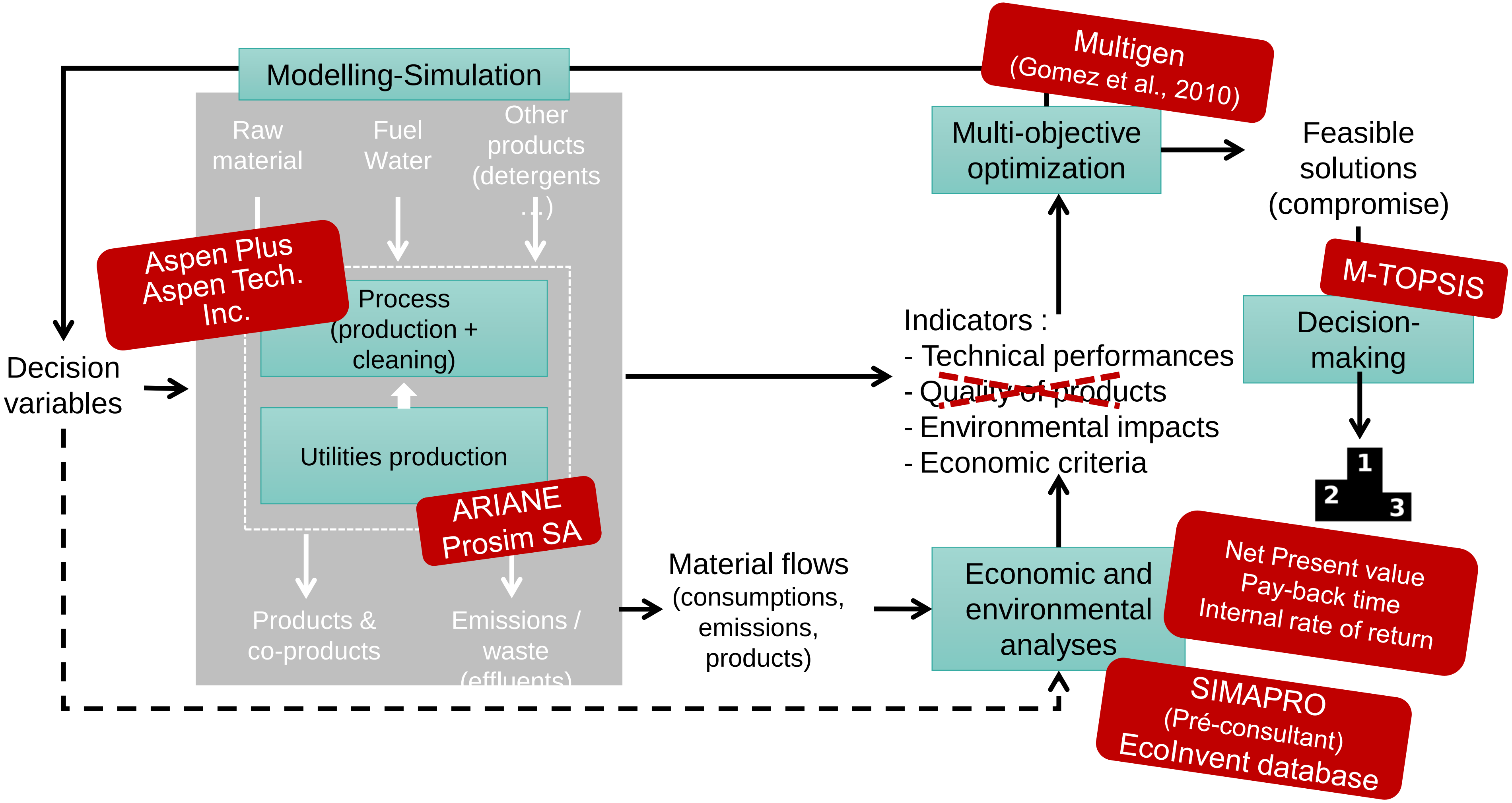
Choice of Aspen Plus

- Coupling with optimization algorithms
- Integration of data/correlations/ models in the software by users

Madoumier et al. JFE 2015
Madoumier et al., FBP, 2020
Azzaro-Pantel et al., FBP, 2022

Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator



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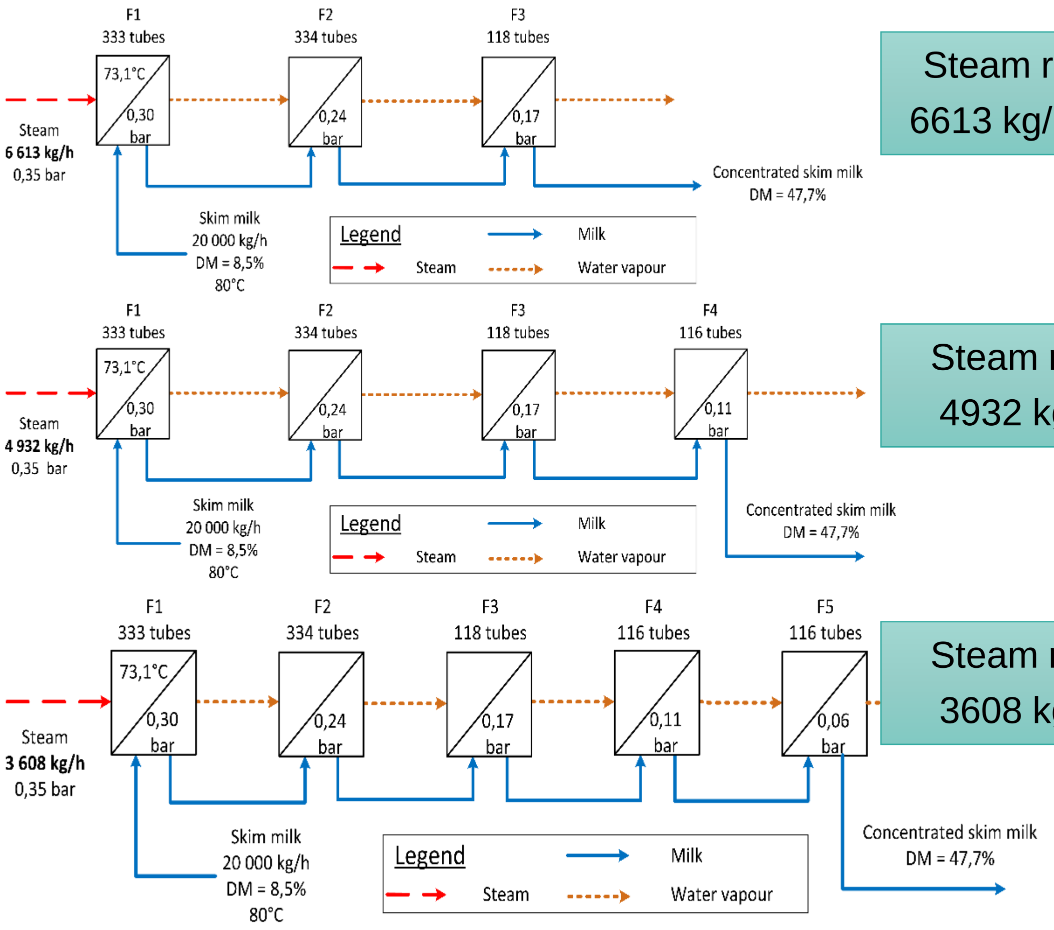
Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator

→ Choice of the number of effects



Steam requirement:
6613 kg/h (**0 – Ref**)

Steam requirement:
4932 kg/h (**-25%**)

Steam requirement:
3608 kg/h (**-45%**)

Parameters of the Process
Falling-film evaporator
20 t/h of treated skimmed milk 50 % DM of the concentrate
Constant CIP sequences
Primary source of energy = natural gas
Variables in design
Number of effects ([3 ; 4 ; 5])

Madoumier et al. JFE 2015
Madoumier et al., FBP, 2020
Azzaro-Pantel et al., FBP, 2022

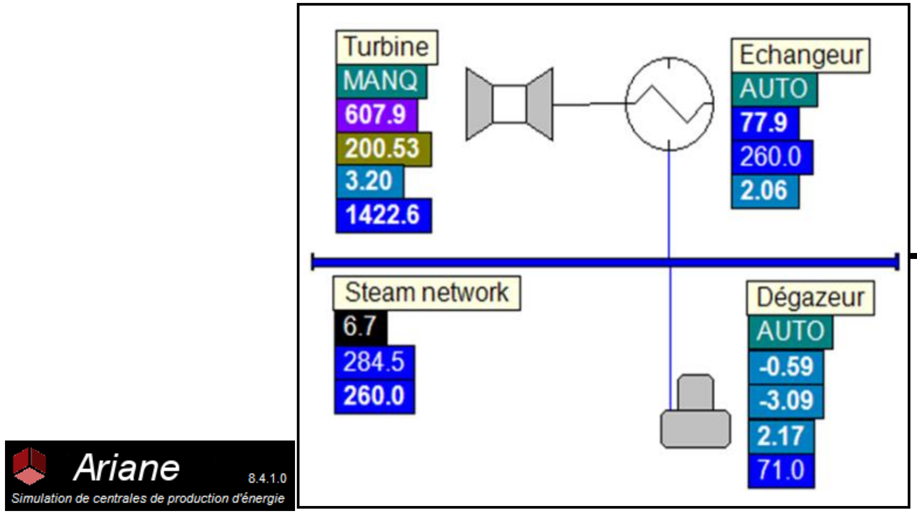
Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator

→ Choice of the primary source of energy

Parameters of the Process
Constant evaporation process
20 t/h of treated skimmed milk 50 % DM of the concentrate
Constant CIP sequences
Variables in design
Fuel : natural gas, oil, wood chips

Natural Gas
Oil
Wood Chips



→ Calculation of utility consumption (water, fuel, etc., electricity) combustion emissions (carbon dioxide, nitrogen oxides, etc.) according to energy demand of the evaporator → environmental and economic impacts

Madoumier et al. JFE 2015
Madoumier et al., FBP, 2020
Azzaro-Pantel et al., FBP, 2022

Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator

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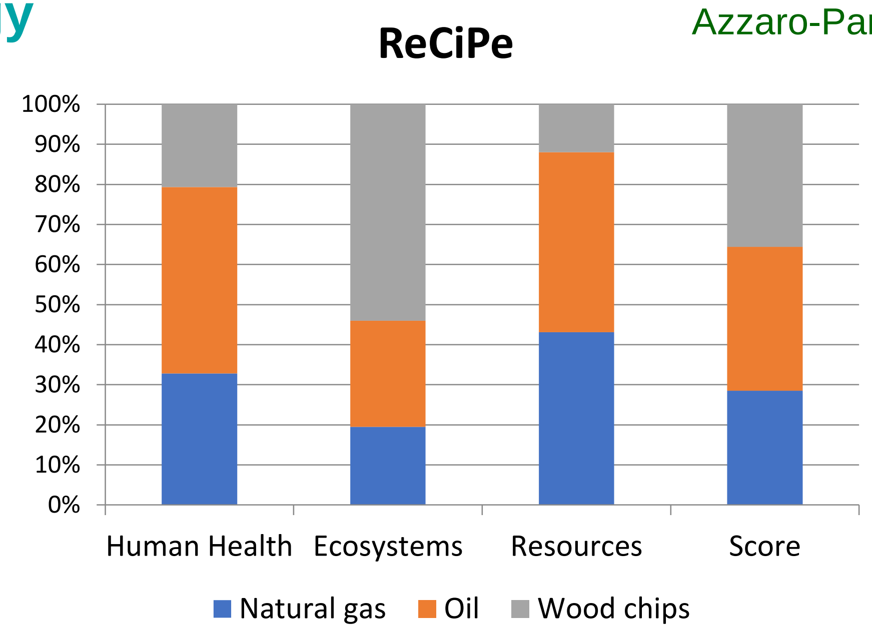
Azzaro-Pantel et al., FBP, 2022

→ Choice of the primary source of energy

Environmental criteria



Economic criteria

	Net Present value (+) (M€)	Pay-back time (-) (year)	Internal Rate of Return (+) (%)
Natural Gas (reference)	8.26	3.6	47
Oil	9.34 (+13%)	3.4 (-7%)	51 (+9%)
Wood chips	9.54 (+16%)	4.0 (+9%)	42 (-10%)

Eco-design strategy n° 3 : Multi-objective optimization

Case study: evaporation of milk / process simulator

→ Choice of the primary source of energy

Multicriteria analysis (M-TOPSIS)

	Combustible		
	Natural gas	Oil	Wood chips
Net Present Value, Single score ReCiPe	1	3	2
3 economic criteria, 3 Endpoint scores ReCiPe	2	3	1

Madoumier et al. JFE 2015
Madoumier et al., FBP, 2020
Azzaro-Pantel et al., FBP, 2022

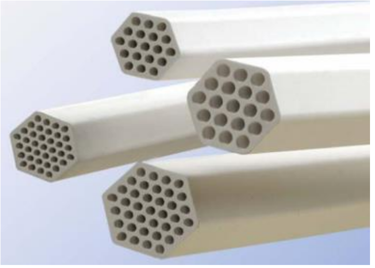
Eco-design strategy n° 3 : Multi-objective optimization

Case study: microfiltration of milk / knowledge integration

Belna et al. JFE, 2020
Belna et al, ESWA, 2022
Baudrit et al., IJAEIS, 2022

Microfiltration 0.1 µm of milk

- ❑ Fractionation of the two major groups of dairy proteins
  → (cheese manufacture, production of ingredients)



UTP, Uniform Transmembrane Pressure System (Sandblöm, 1974)

Membrane with permeability gradient

Spiral wound

- ❑ Various options for microfiltration design→ conflicting objectives

- ❑ No optimization of MF design integrating conflicting objectives
- ❑ Lack of predictive MF performance models

Input of Artificial Intelligence

> Use of « Expert knowledge integration » to design microfiltration

Eco-design strategy n° 3 : Multi-objective optimization

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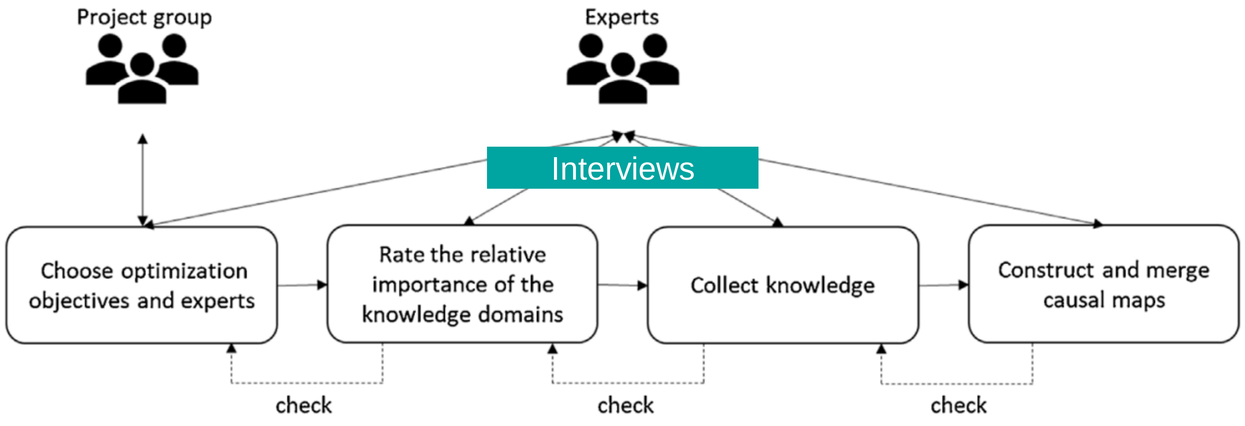
Case study: microfiltration of milk / knowledge integration



Hobballah et al. Expert Syst. (2018)

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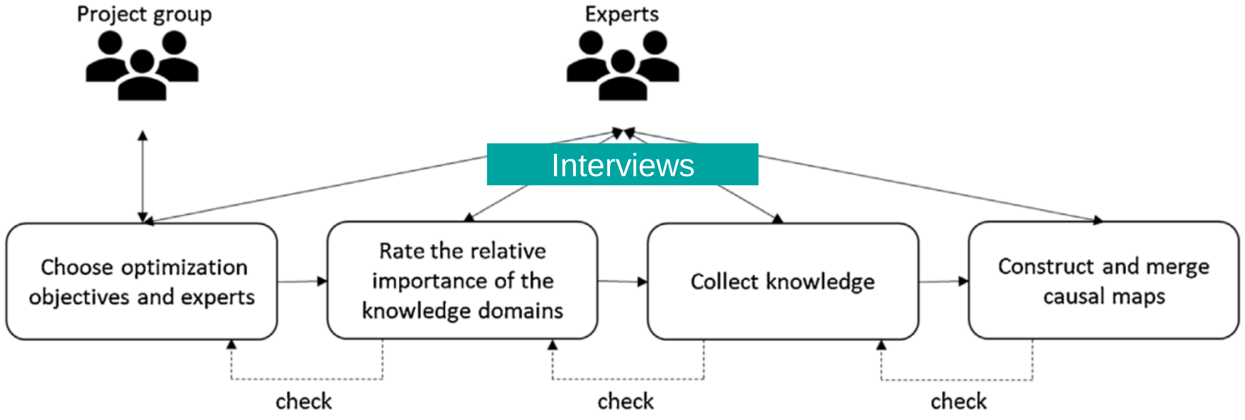

- 5 optimisation objectives
- 5 decision variables
- 31 intermediate variables

$\max CD_{CN,r}$
Casein concentration in retentate on dry basis

$\max CD_{SP,p}$
Serum protein concentration in permeate on dry basis

$\max \eta_p$
Serum protein protein recovery rate

$\min CI$
Investment cost

$\min CPR$
Productionc cost

Casein micelles
Serum proteins

Hobballah et al. Expert Syst. (2018)

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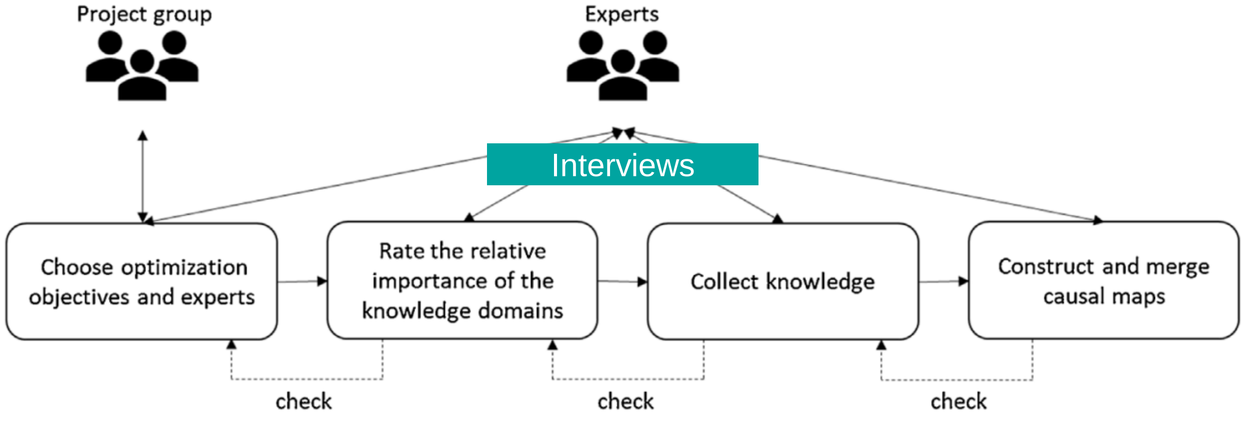

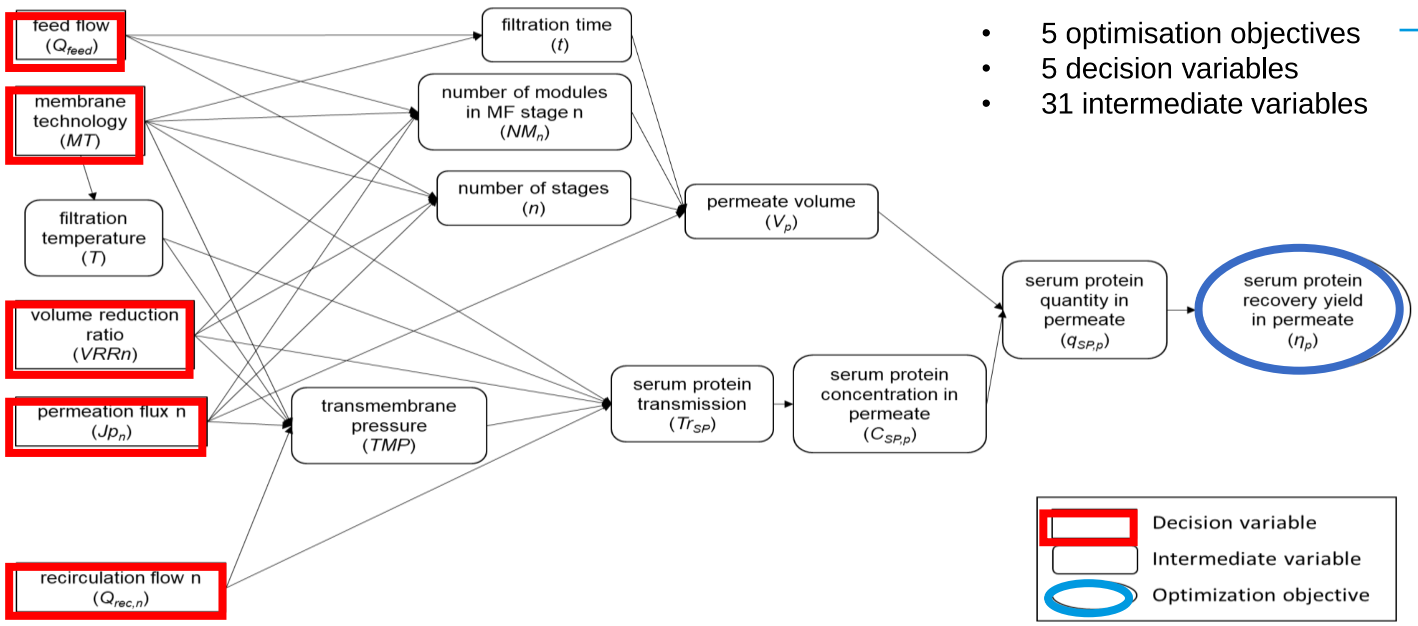

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Productionc cost

Casein micelles
Serum proteins

$$\eta_p = \frac{q_{SP,p}}{q_{SP,milk}} = \frac{C_{SP,p}\left(V_{feed} - \left(\frac{V_{feed}}{VRR}\right)\right)\rho_p}{C_{SPmilk} \cdot V_{feed} \cdot \rho_{milk}}$$

Hobballah et al. Expert Syst. (2018)

Eco-design strategy n° 3 : Multi-objective optimization

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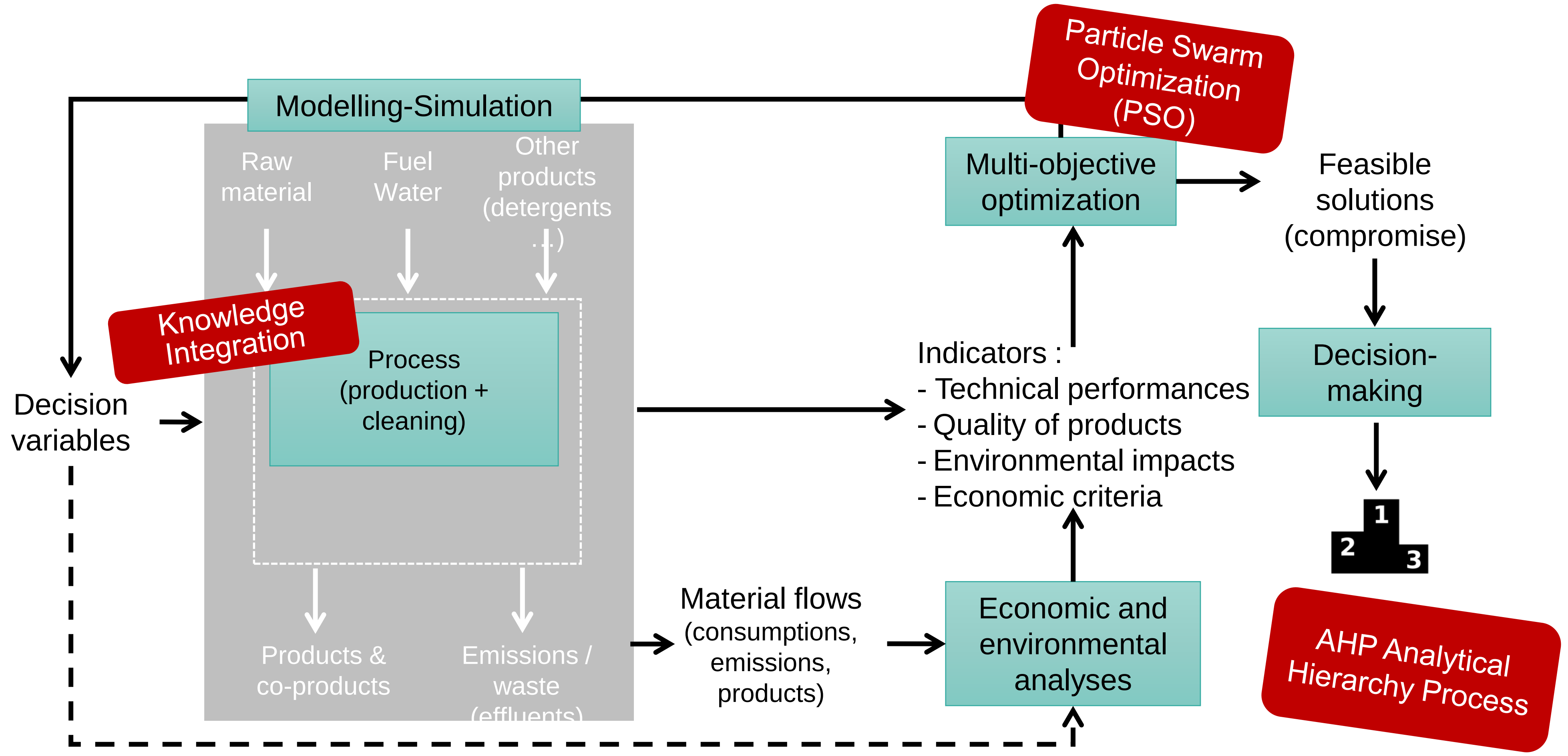
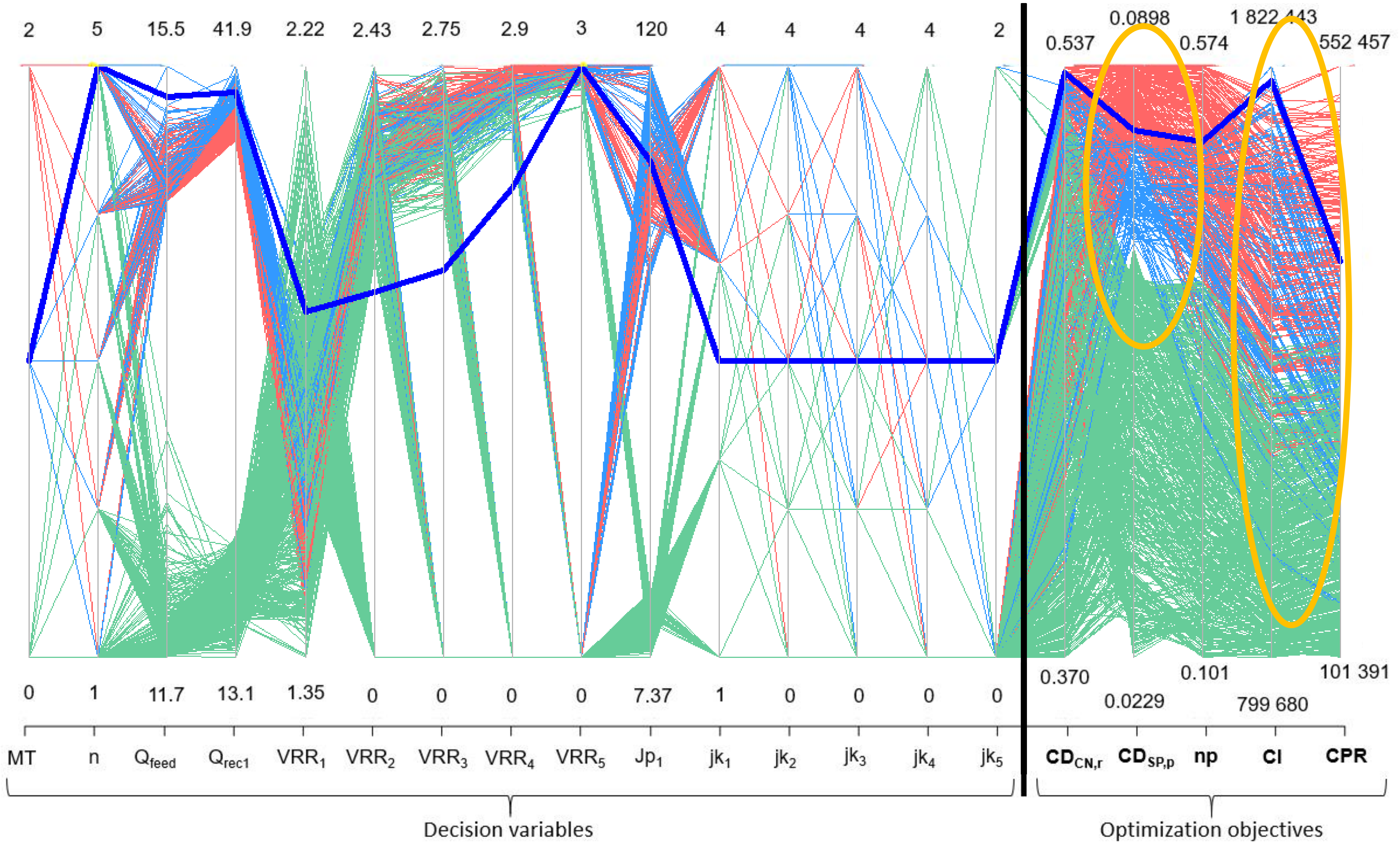


> Results

Belna et al, ESWA, 2022



- Over 1000 Pareto-optimal solutions
- Consistent with literature and industrial practices
- Trade-off in the choice of MT: Ceramic membranes compared to polymeric :

Technical objectives **more efficient**

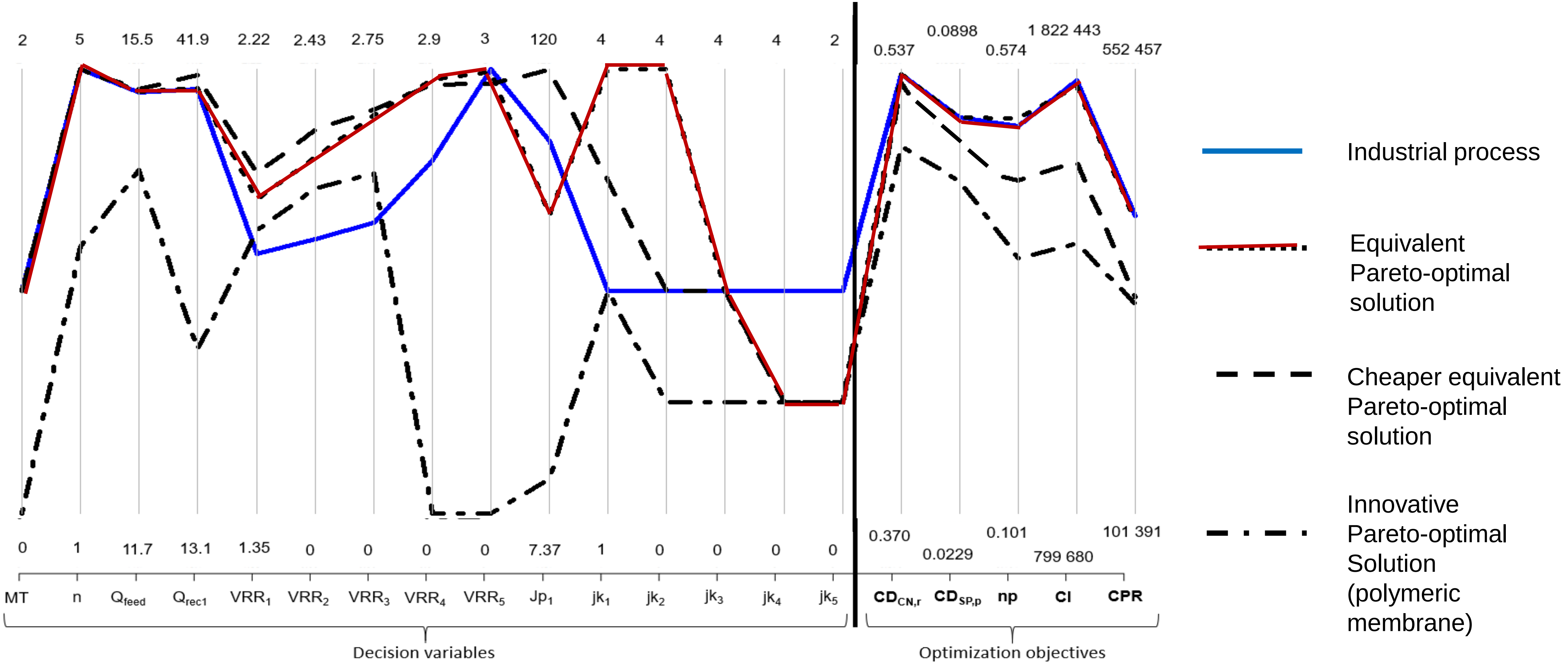
BUT

More expensive

Q_{feed} ($m^3.h^{-1}$) ; Q_{rec1} ($m^3.h^{-1}$) ; Jp_1 ($L.h^{-1}.m^{-2}$) ; CD_{CNr} ($g.kg^{-1}$ DM) ; CD_{SPp} ($g.kg^{-1}$ DM) ; CI (€) ; CPR (€)

> Particular Pareto-optimal solutions analysis

Belna et al, ESWA, 2022



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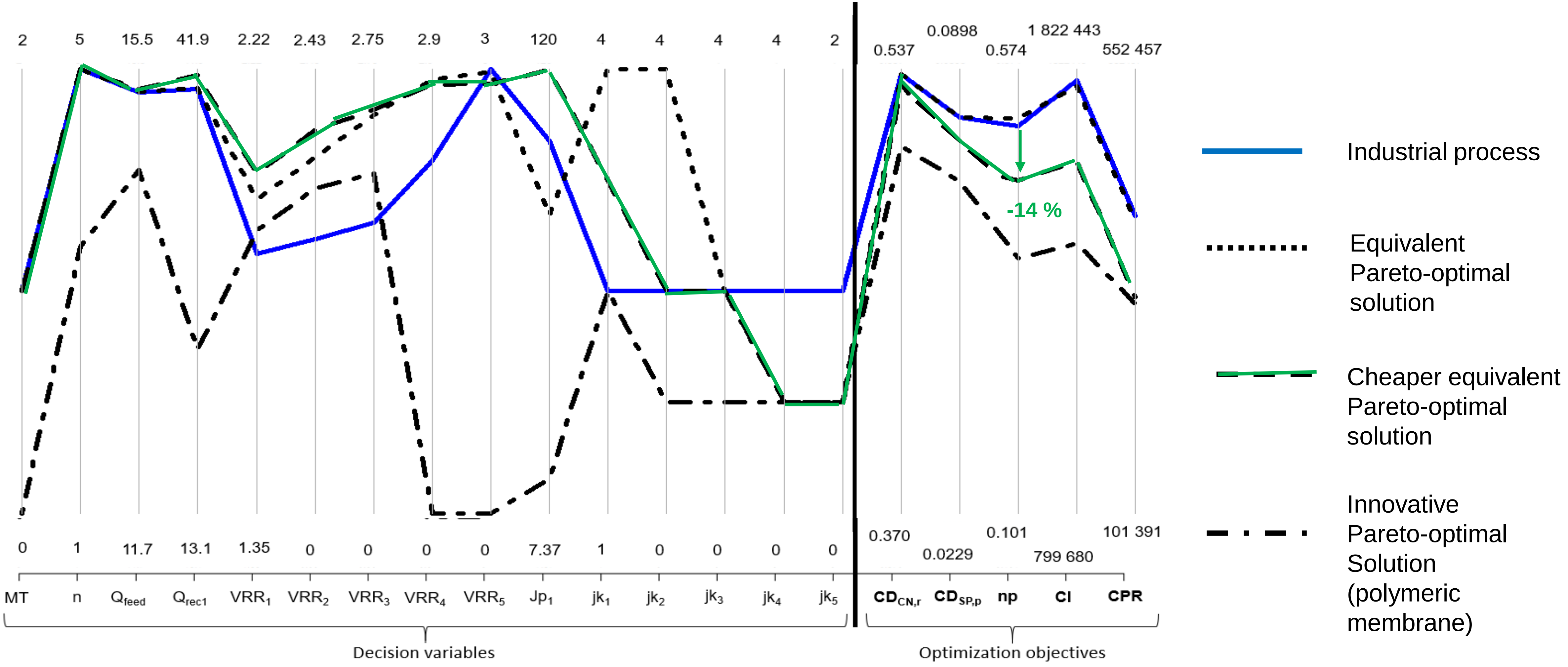

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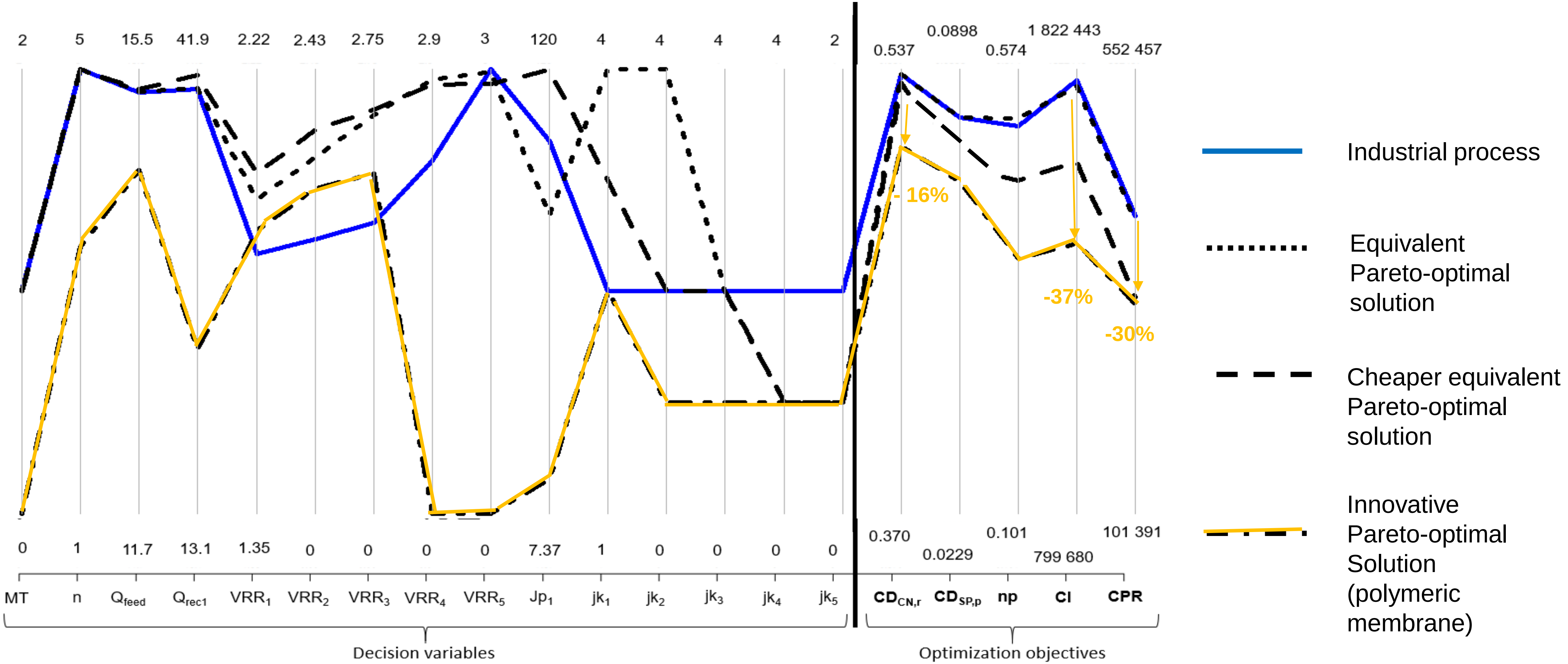

Q_{feed} ($m^3.h^{-1}$) ; Q_{rec1} ($m^3.h^{-1}$) ; Jp_1 ($L.h^{-1}.m^{-2}$) ; CD_{CNr} ($g.kg^{-1}$ DM) ; CD_{SPp} ($g.kg^{-1}$ DM) ; CI (€) ; CPR (€)

> Take-home messages

1/ Strategies of eco-design of food processing have emerged for < 20 years
→ Different levels of strategies are possible
→ Inspiration can be taken from other industrial sectors and disciplines

2/ Holistic multi-objective optimization methods are relevant and can be used to improve the design of food process taking into account sustainability criteria

3/ Efforts are still needed

- **To improve the methodologies, the collection, storage and update of data, and user-friendly tools**
- **To improve the models and predictive approaches which could help develop multi-objective optimisation methods for processes**
- **To better implement these approaches in the food supply chain**

FAIRCHAIN

https://www.fairchain-h2020.eu/

Thank you for your attention !

And to all contributors …

**Maëllis Belna, Martial Madoumier, Nicolas AlvarezAmadou Ndiaye, Franck Taillandier,
Patrice Buche, Cédric Baudrit, Christophe Fernandez
Nadine Leconte, Fabienne Lambrouin, Maksym Loginov
Gaëlle Tanguy, Pierre Schuck**