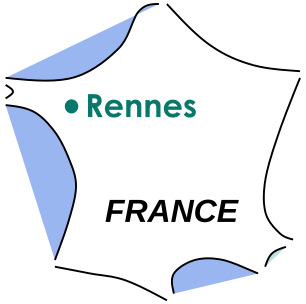
Sustainability in the food processing : How membrane separation processes contribute

Geneviève Gésan-Guiziou

Sustainability in the food processing : How membrane separation processes contribute

Geneviève Gésan-Guiziou

INRAE, Institut Agro
UMR 1253 Science et Technologie du Lait et de l'Oeuf
genevieve.gesan-guiziou@inrae.fr
www.rennes.inrae.fr/stlo

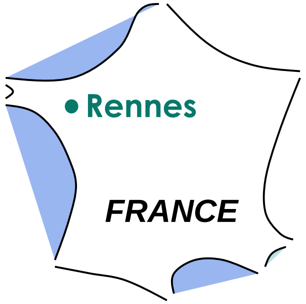


dairy

Sustainability in the food processing : How membrane separation processes contribute

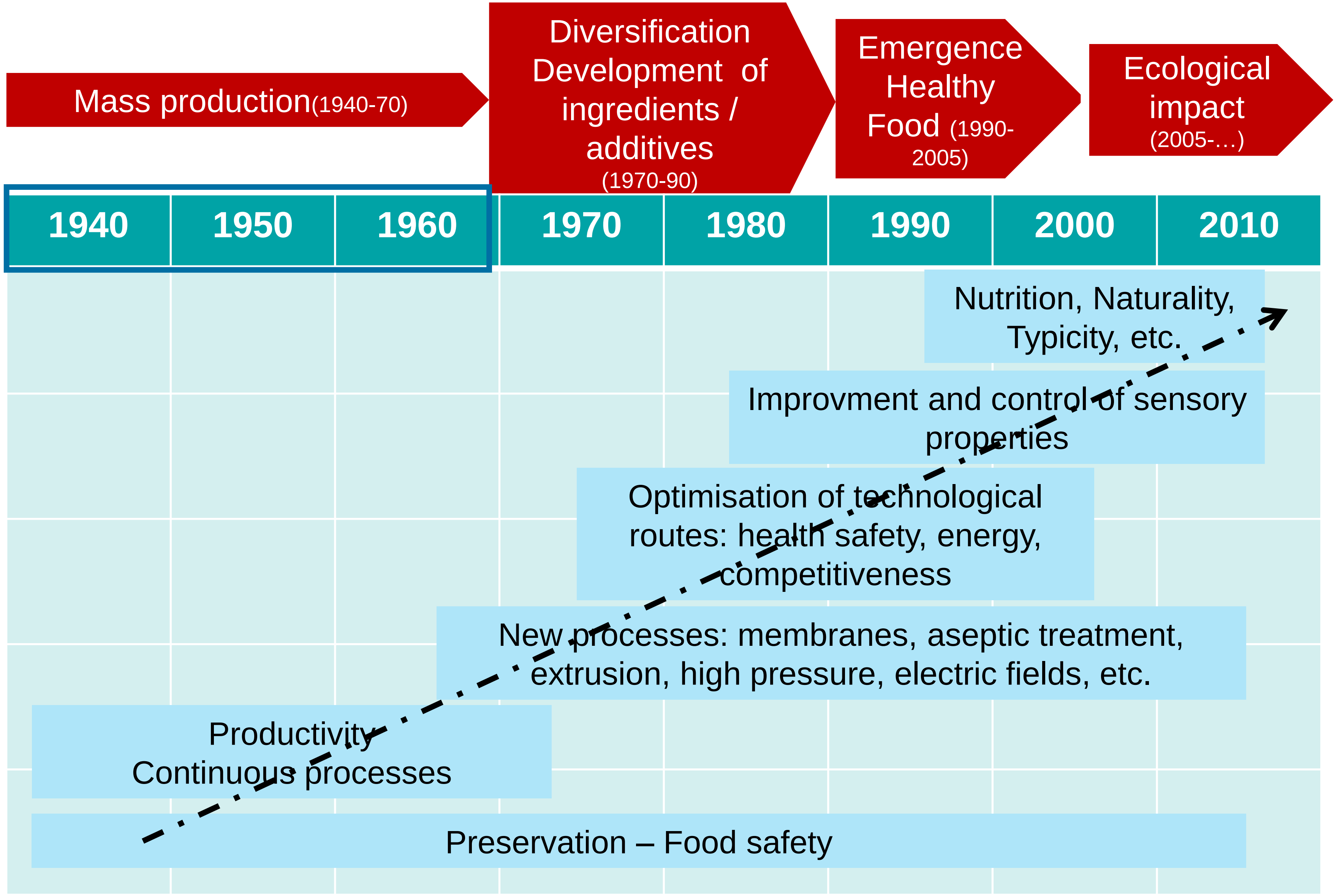
Geneviève Gésan-Guiziou

INRAE, Institut Agro
UMR 1253 Science et Technologie du Lait et de l'Oeuf
genevieve.gesan-guiziou@inrae.fr
www.rennes.inrae.fr/stlo



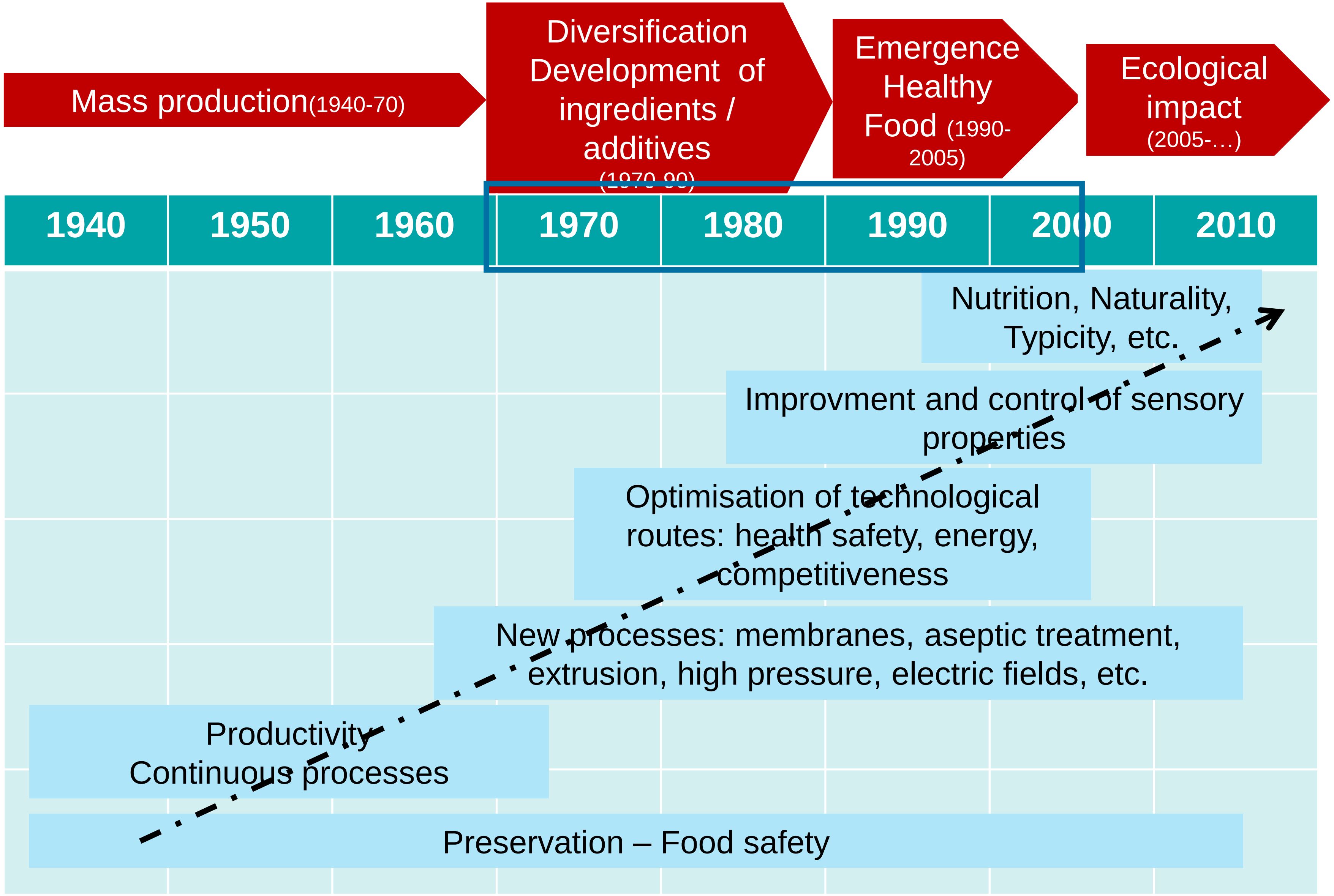
STLO
RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité
INRAE
L'INSTITUT agro Rennes Angers
Qualiment

Context / Evolution of food processing



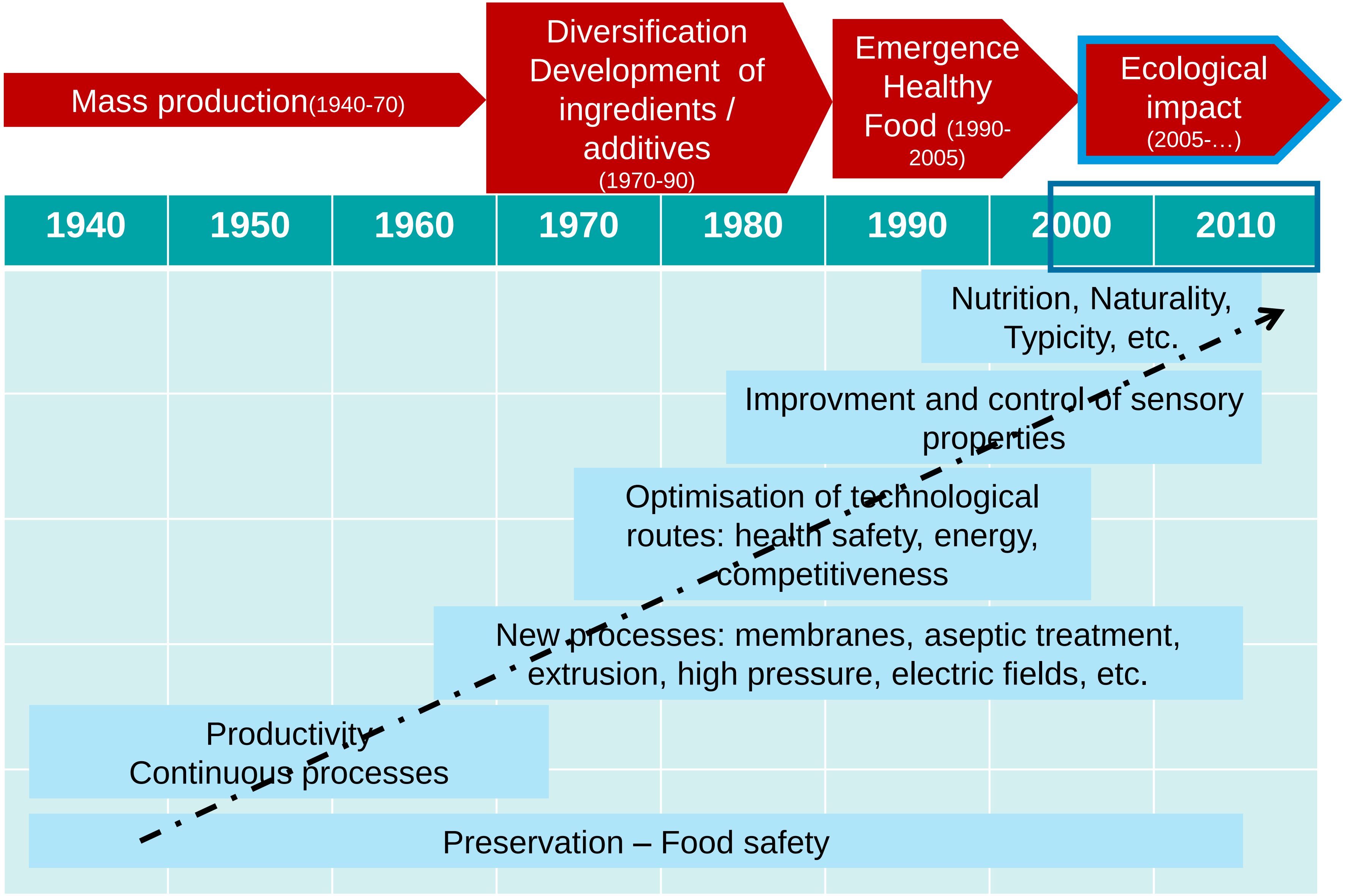
Trystram, 2011

Context / Evolution of food processing



Trystram, 2011

Context / Evolution of food processing



Trystram, 2011

Why integrate sustainability concepts into food processing ?

Agri-food supply chain

Production (agriculture) → Raw materials → **Raw material processing** → Products Co-products → Distr. → **Use** → Disposal Recycling

Processing

Agriculture

Roy et al., 2009; Berners-Lee et al. 2012

Why integrate sustainability concepts into food processing ?

Agri-food supply chain

Production (agriculture) → **Raw materials** → **Raw material processing** → **Products Co-products** → **Distr.** → **Use** → **Disposal Recycling**

Processing

Agriculture

50% of carbon footprint at farm level for 95% of products

Roy et al., 2009; Berners-Lee et al. 2012

Why integrate sustainability concepts into food processing ?

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

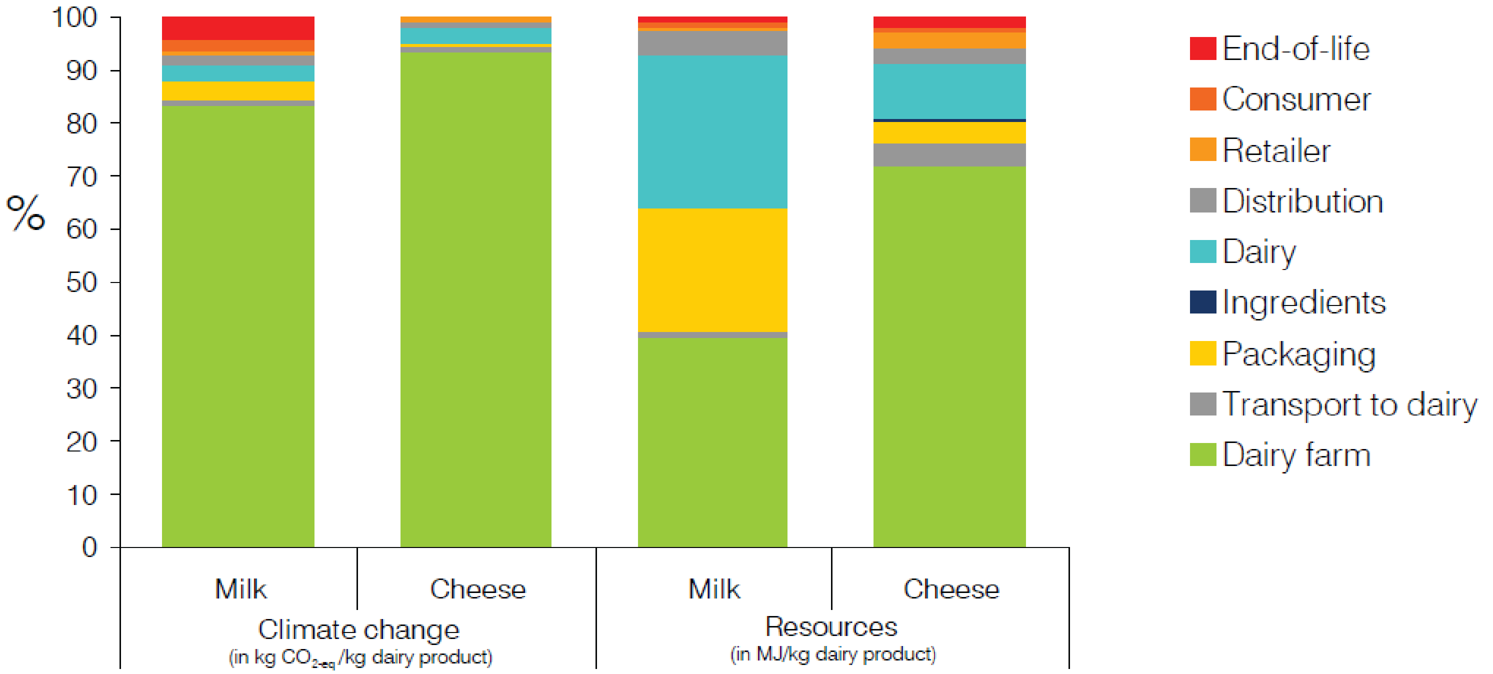


Figure 0.2: Contribution of the different life cycle phases for climate change and resources for 1 kg of milk and 1 kg of cheese.

IDF Bull (2009) n°436

→ **Req : Conclusions differ depending on the environmental indicator you use**

Why integrate sustainability concepts into food processing ?

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

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

Why integrate sustainability concepts into food processing ?

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

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

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

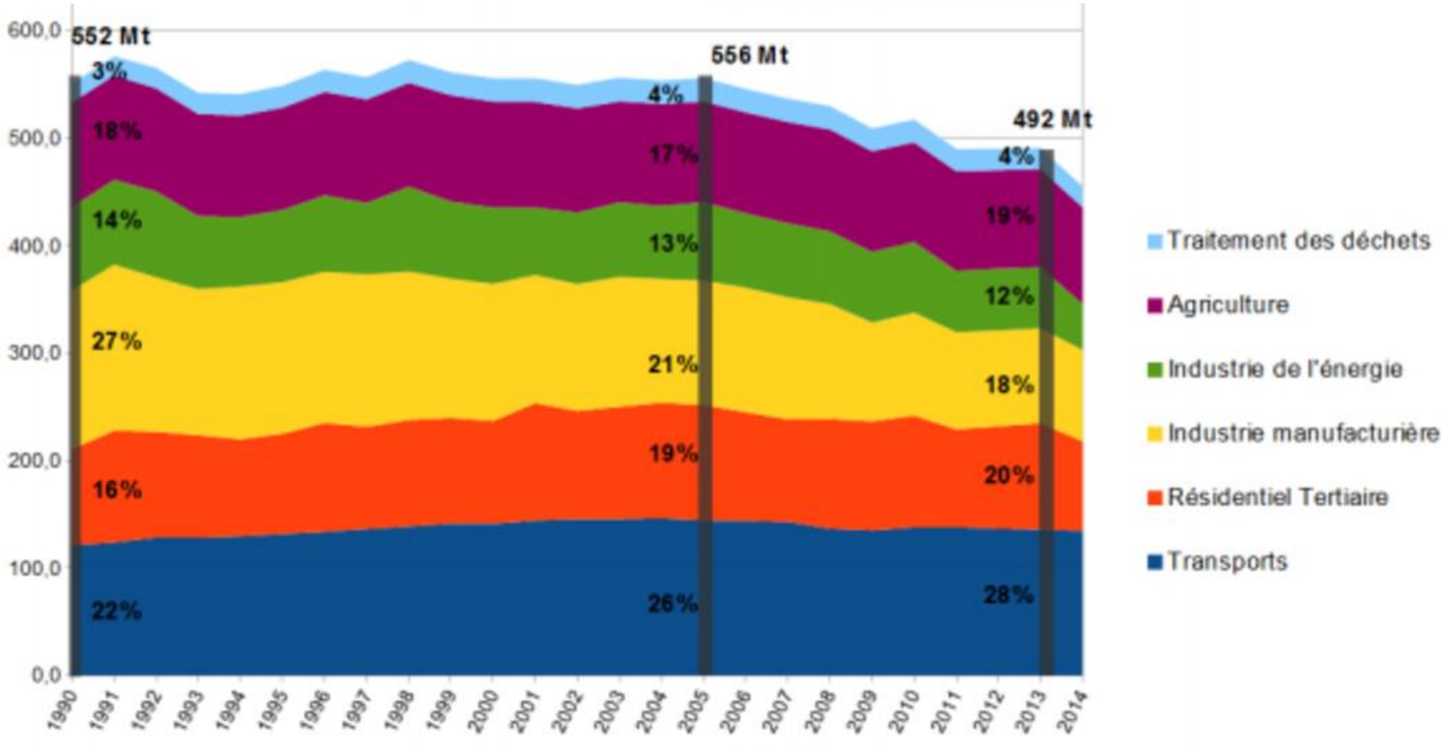
- evolving regulatory framework : e.g. Reach, ecological labelling
- increase of consumer awareness

Encouragement by COP 21 in Paris, 6 years ago

Why integrate sustainability concepts into food processing ?

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

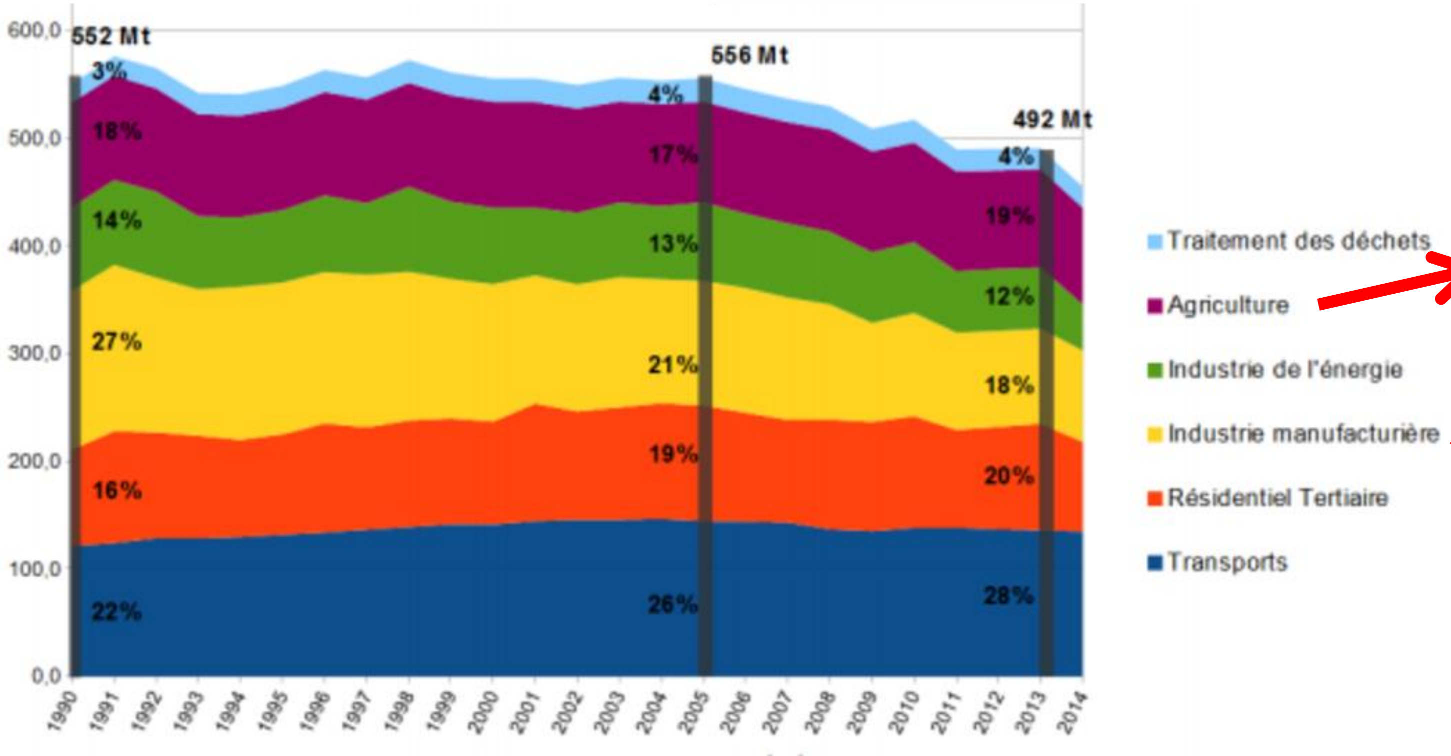
Evolution of Greenhouse gas emissions in France from 1990 and 2013



Why integrate sustainability concepts into food processing ?

Much effort has to be done 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

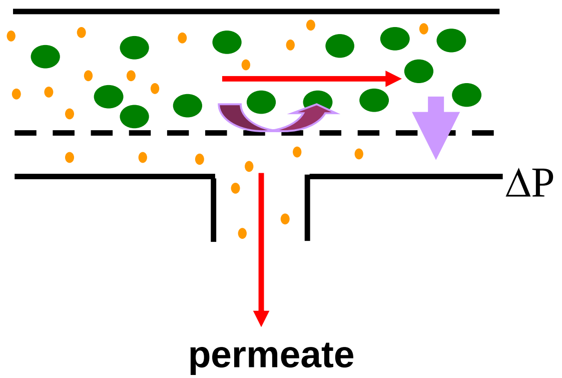
-24 % within the next 10 years ; and -75 % by 2050

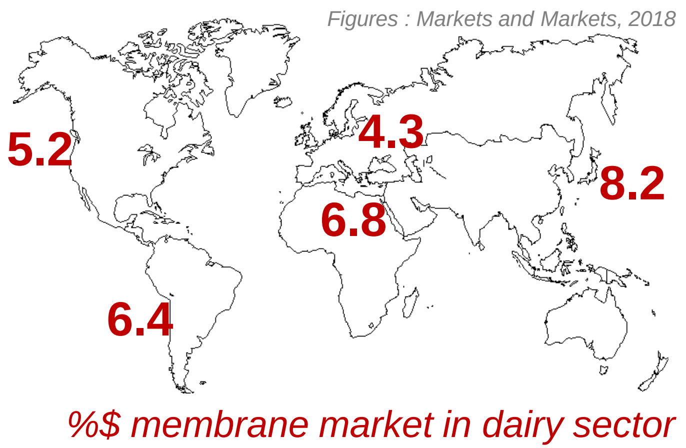
Objective

- Present sustainability strategies (3 levels) adapted to food processing
- Illustrate these strategies with membrane processes

Objective

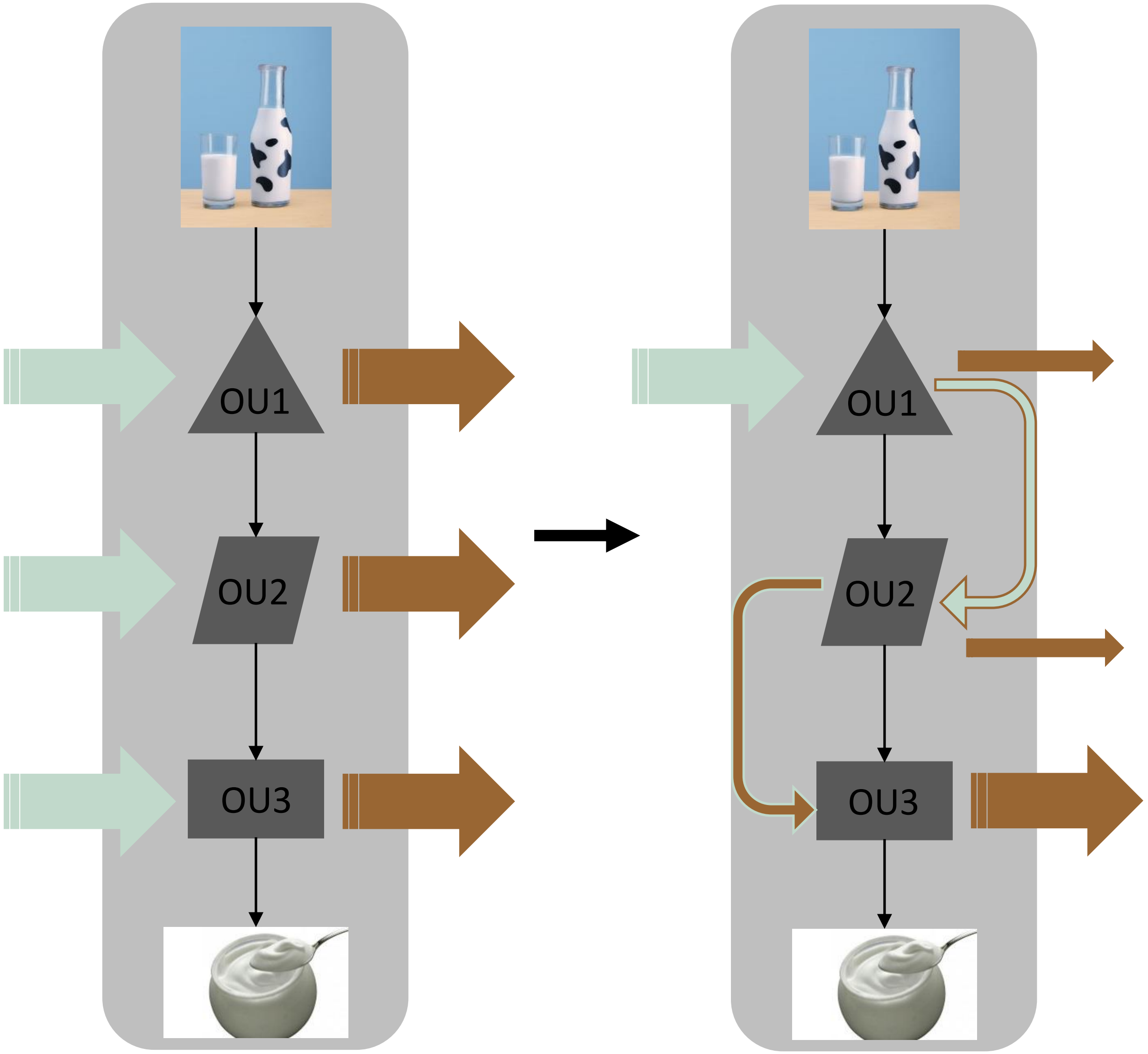
- Present sustainability strategies (3 levels) adapted to food processing
- Illustrate these strategies with membrane processes





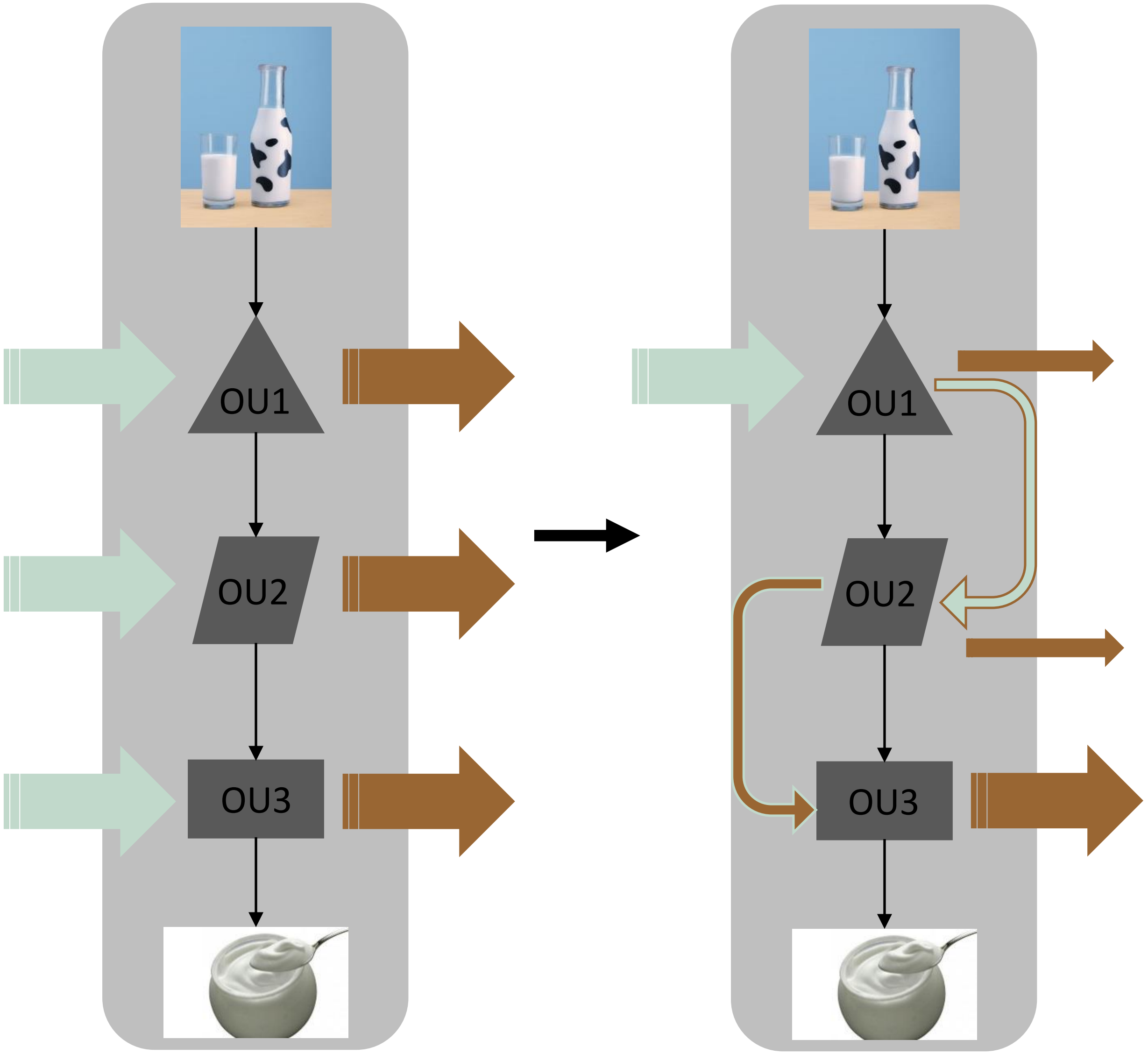
Largely used operations in the food sector (extraction / valorization of bioreources/ non-thermal stabilization / treatment of effluents, etc.)
Membrane market in increasing
Single-use of cleaning solutions
→ high volume of water
→ high environmental impacts

Sustainability strategy n°1: Minimization of resources



- Common-sense measures
- Reuse / redistribution of the flows making use of intelligent design methods (Pinch, exergy analysis)
- Modifying operating conditions (temperature, flux < critical flux)

Sustainability strategy n°1: Minimization of resources



- Common-sense measures
- Reuse / redistribution of the flows making use of intelligent design methods (Pinch, exergy analysis)
- Modifying operating conditions (temperature, flux < critical flux)

- Single action on water or energy consumption
- Does not consider modifications of food product
- Does not allow search for a global optimum

Level of sustainability n°1: Minimization of resources by reuse / recycling

Reuse/Recycling → Treatment of fluids by membrane processes to meet the quality requirements

- Minimization of water consumption:
  - Ex: NF, RO to treat ultrafiltrates and nanofiltrates and reuse water

- Regeneration of chemicals (and minimization of water consumption): recycling of caustic soda solutions after filtration (MF, UF)

→ Reduction of cleaning solutions withdrawal to the WWTP

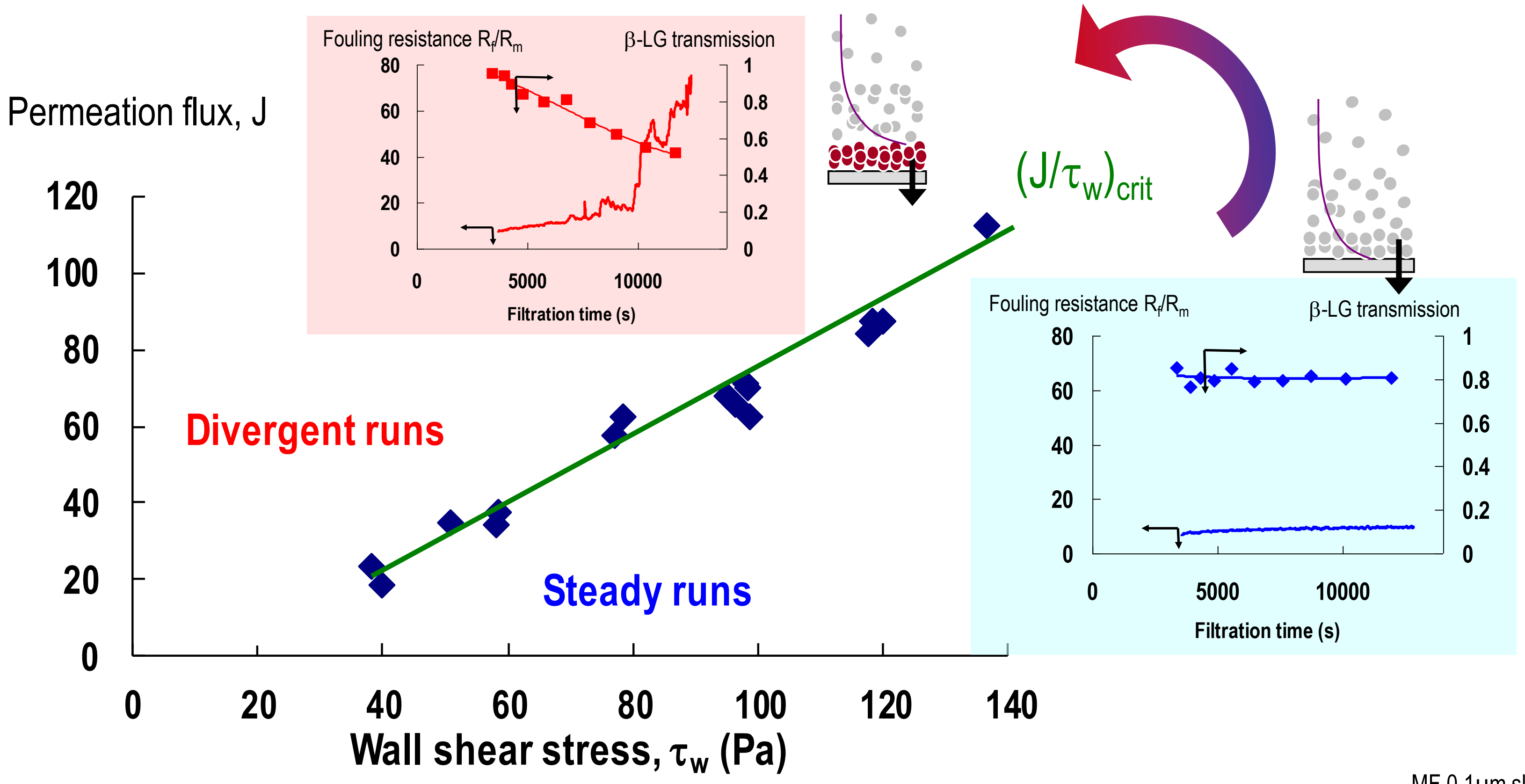
(→ Improvment of the quality of the final product (Lower surface tension of recycled contaminated caustic soda solutions / initial solutions))

Sustainability strategy n° 1 : Minimization of resources by operating process under critical flux concepts

The *critical flux concept* : flux below which fouling / deposition is negligibe and above which fouling/ deposition occurs.

Sustainability strategy n° 1 : Minimization of resources by operating process under critical flux concepts

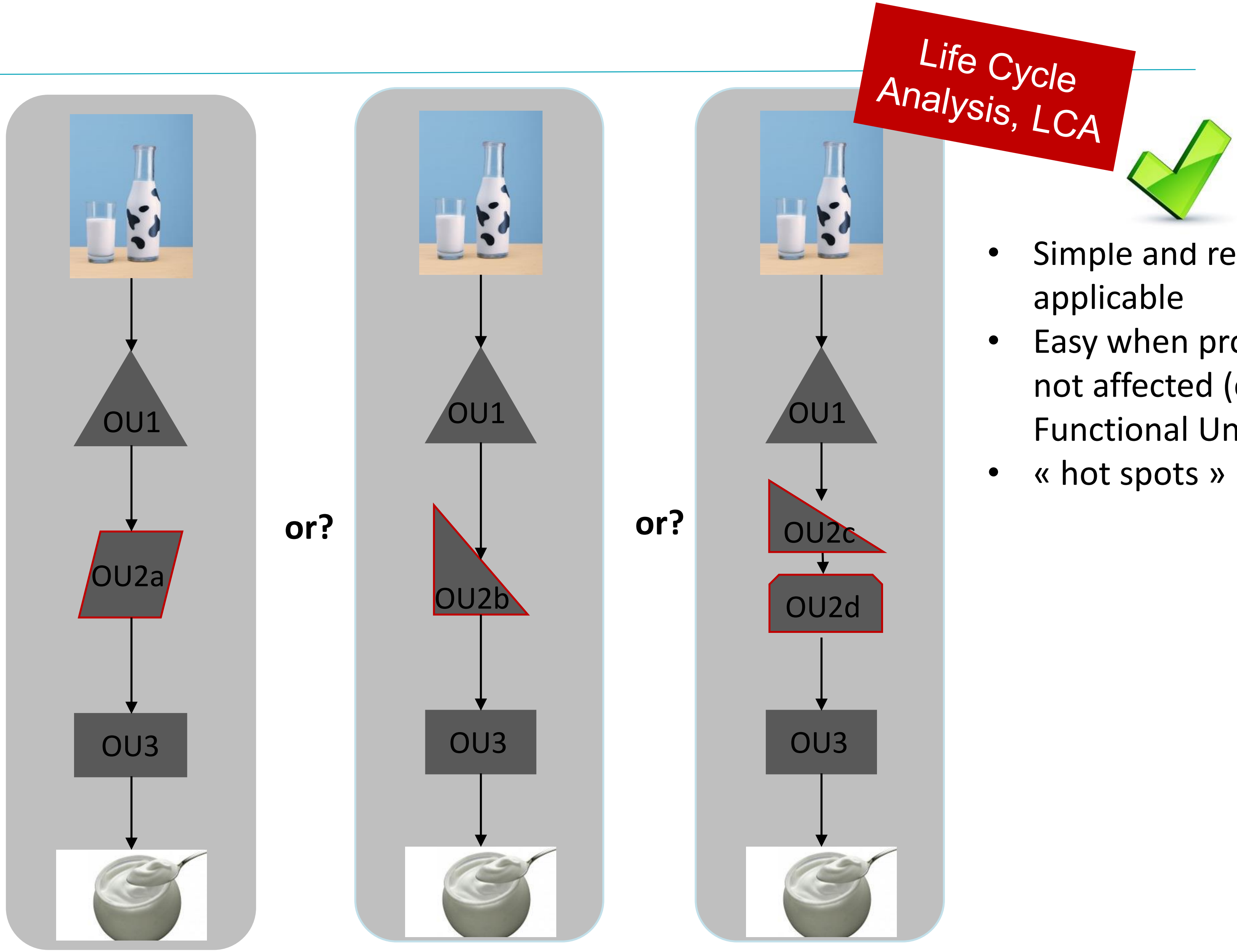
- Operating MF 0.1 µm under critical flux
  - Low and constant fouling and serum protein transmission; less cleaning issues (Ndeye et al, 2013)



The *critical flux concept* : flux below which fouling / deposition is negligibe and above which fouling/ deposition occurs.

MF 0.1µm skimmed milk
Gésan-Guiziou *et al.*, 1999, 2000

Sustainability strategy n° 3 : Comparative assessment of processes

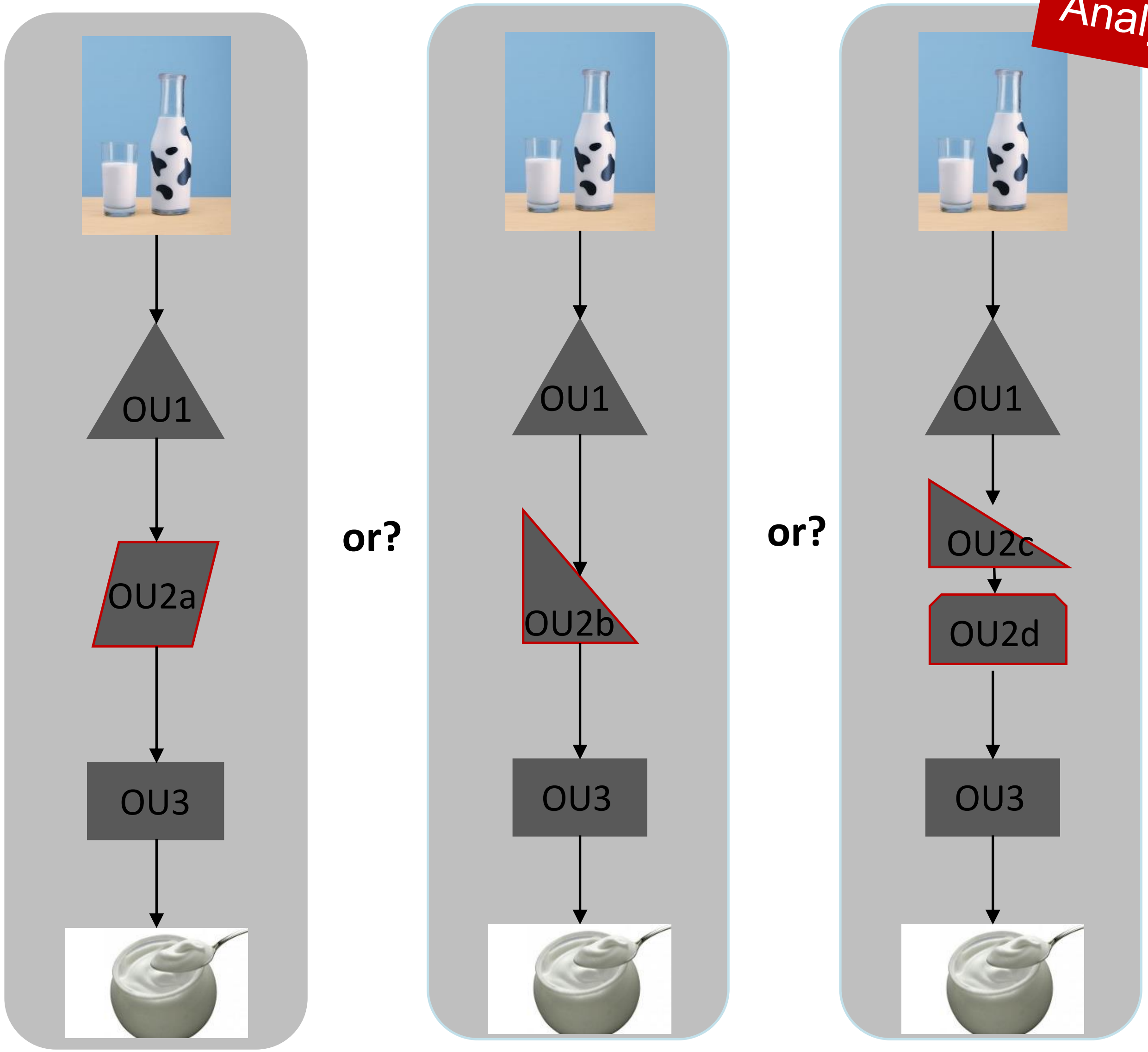


- Simple and readily applicable
- Easy when product is not affected (constant Functional Units)
- « hot spots »

OU: unit operation

Sustainability strategy n° 3 : Comparative assessment of processes

Life Cycle Analysis, LCA

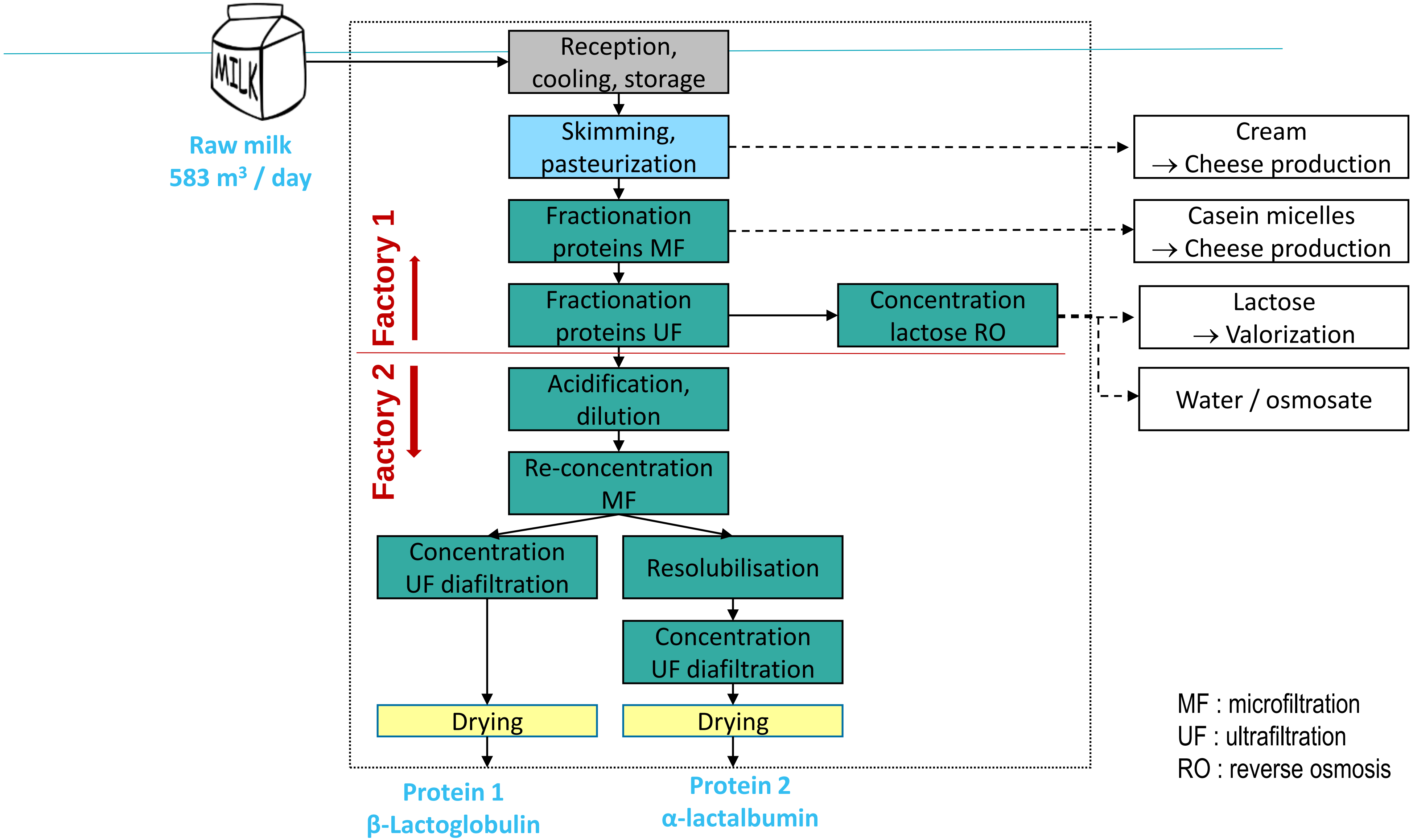


OU: unit operation

- Simple and readily applicable
- Easy when product is not affected (constant Functional Units)
- « hot spots »

- Does not offer solutions for improvement
- Does not allow search for a global optimum

Industrial milk protein fractionation process



Gésan-Guiziou et al. SPT 2019

Industrial milk protein fractionation process

Life Cycle Assessment (LCA)

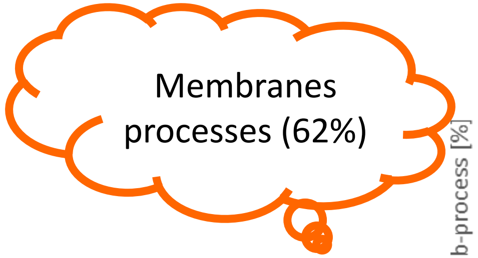
- Attributional LCA
- **DATA** - Ecoinvent 3.0
  - Industrial data, completed with data obtained from experiments performed at the STLO (INRAE) and from use of the drying software SD2P (Schuck et al. 2009)
- **IMPACT ASSESSMENT** : Impact 2002+/ReCiPe + SimaPro 8.0
- **BOUNDARIES** : Gate-to-Gate;

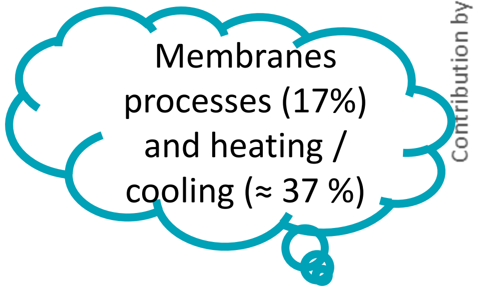
  Sub-processes : production, cleaning, equipment, transport

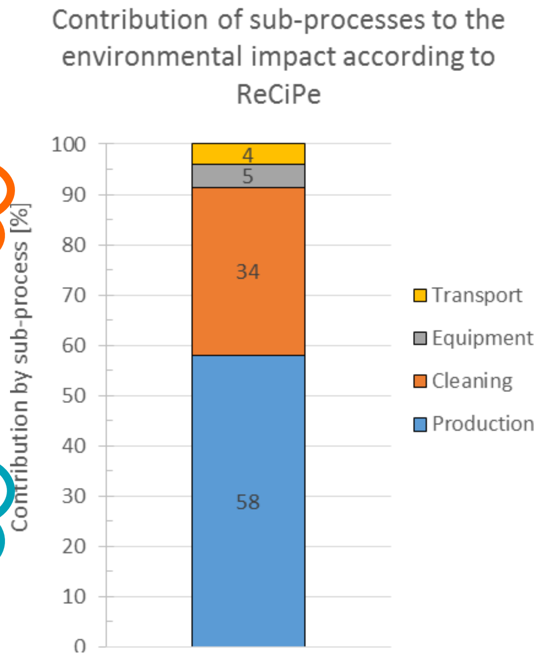
  Exclusions of facilities (building, lightning, etc…)
- **RESULTS**
  - Normalized results (percentaged contribution of the different unit operations to the overall impact)
  - Characterized results (contribution of the individual unit operations to every impact category)
- **FUNCTIONAL UNIT** : whole process (treating 583 m^3 of milk / day)
- No allocation

Industrial milk protein fractionation process

Examples of Results

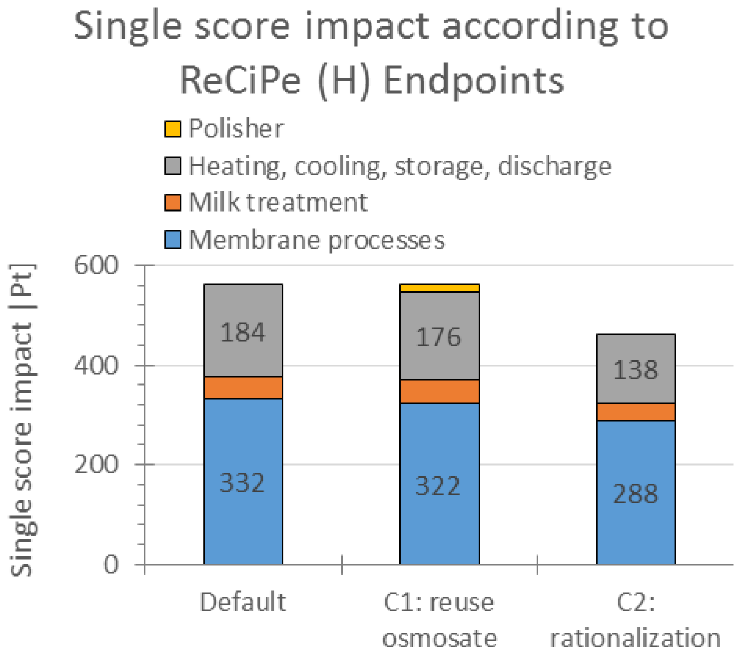






Production (≈ 60 %) and cleaning (≈ 30 %) phases are the main contributors to the overall environmental impact

Impacts of 2 novel cleaning strategies

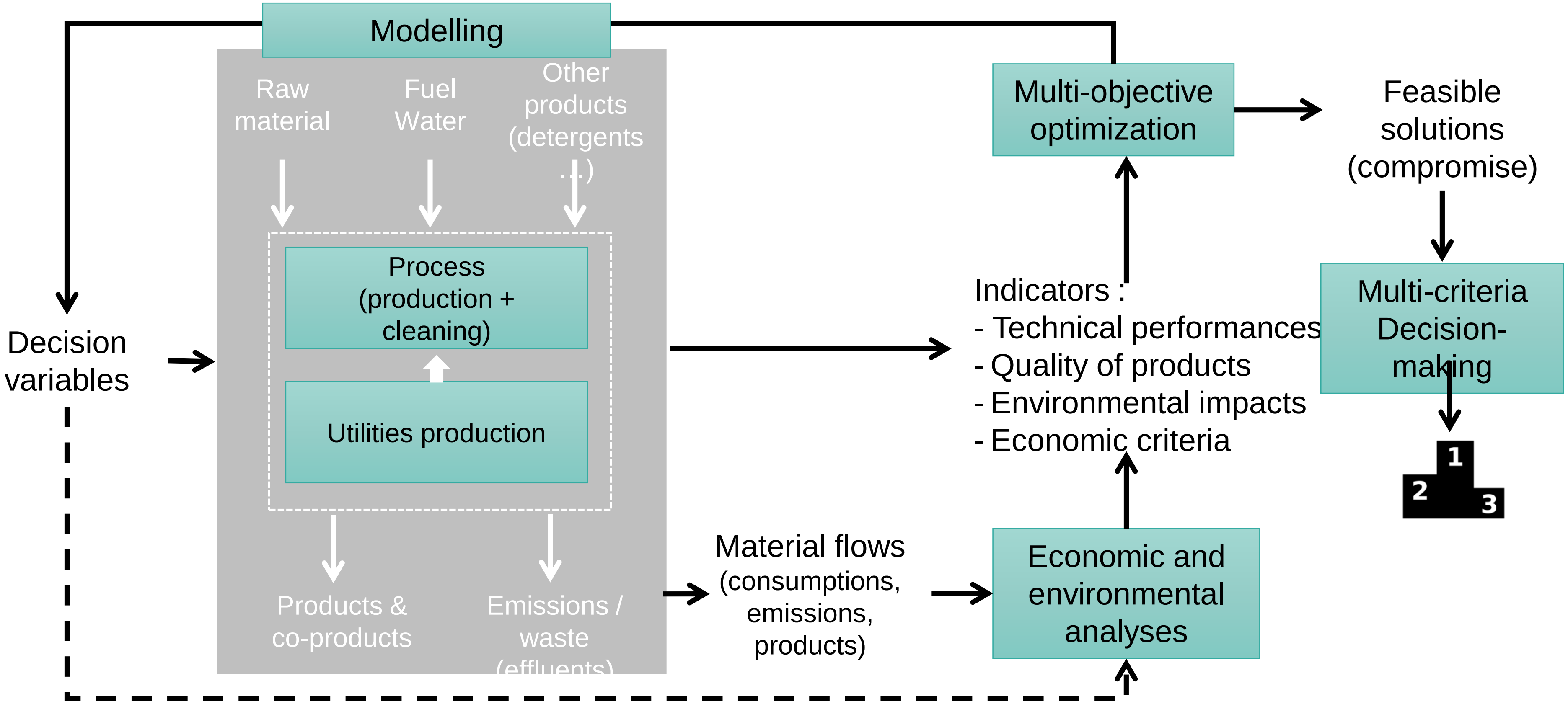


C1: Reutilization of the water from the lactose concentration process → reduction of the freshwater consumption but requirement of a polisher

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

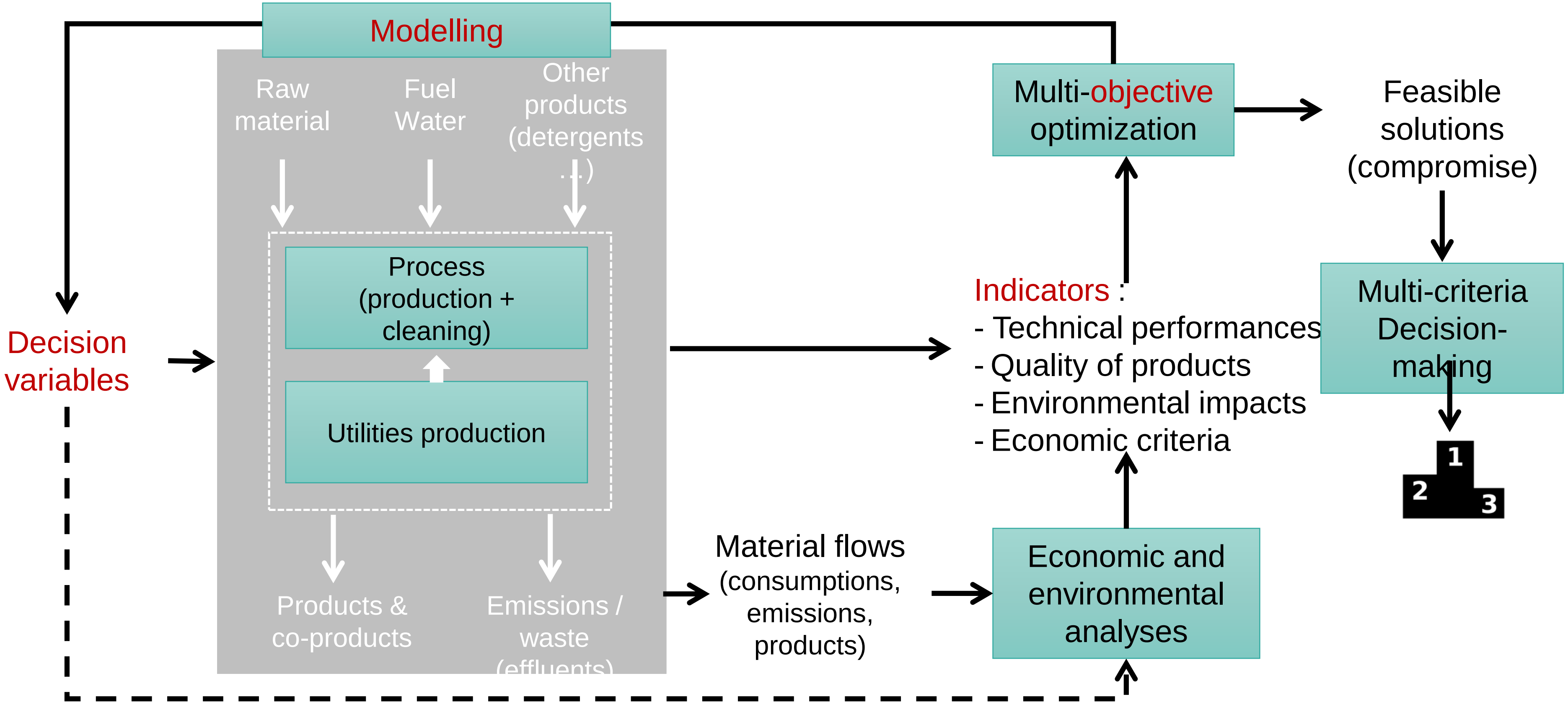
If regarded in detail, the optimization strategies show an improvement for certain categories : ReCiPe: in 12/18

Sustainability strategy n° 4 : Multi-objective optimization



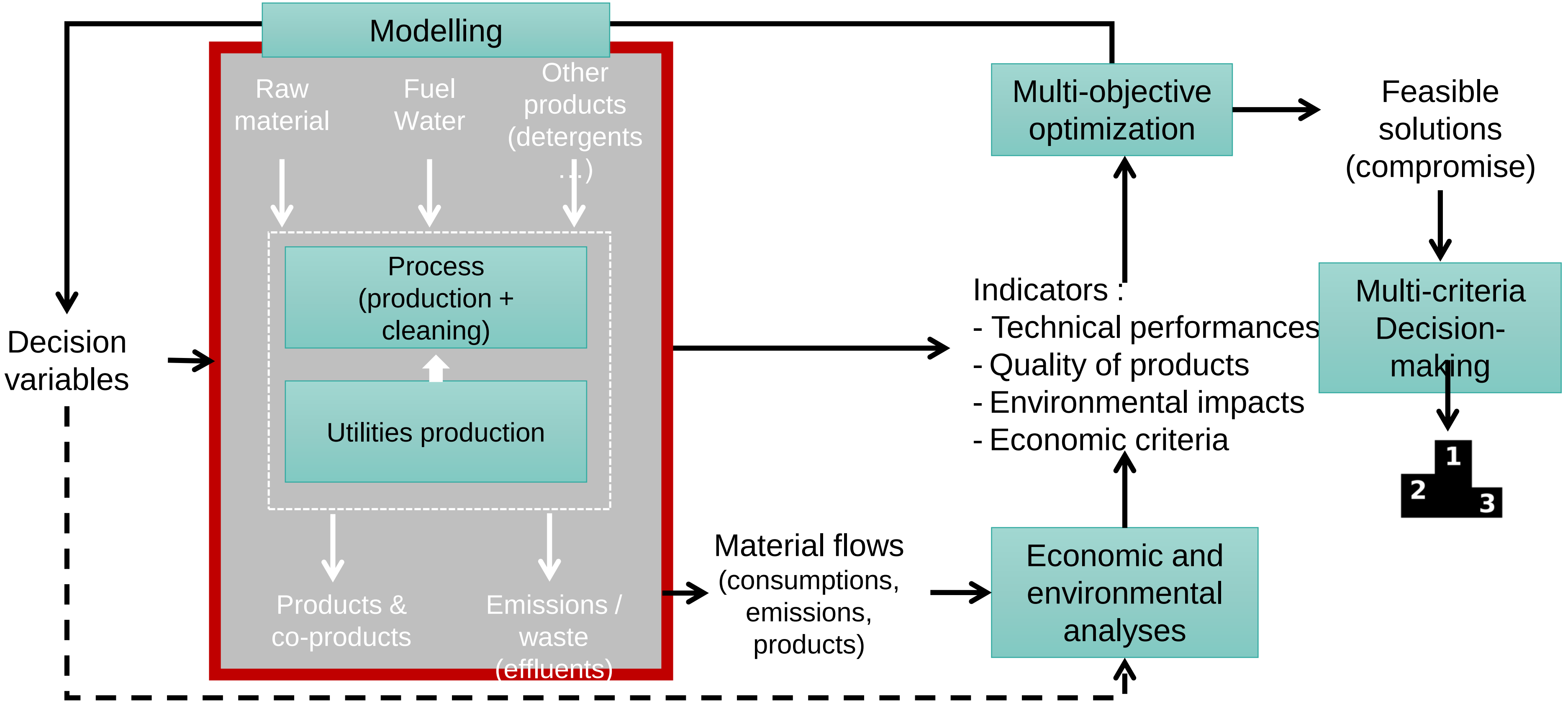
Simultaneous optimization of conflicting objectives

Sustainability strategy n° 4 : Multi-objective optimization



Simultaneous optimization of conflicting objectives

Sustainability strategy n° 4 : Multi-objective optimization



Simultaneous optimization of conflicting objectives

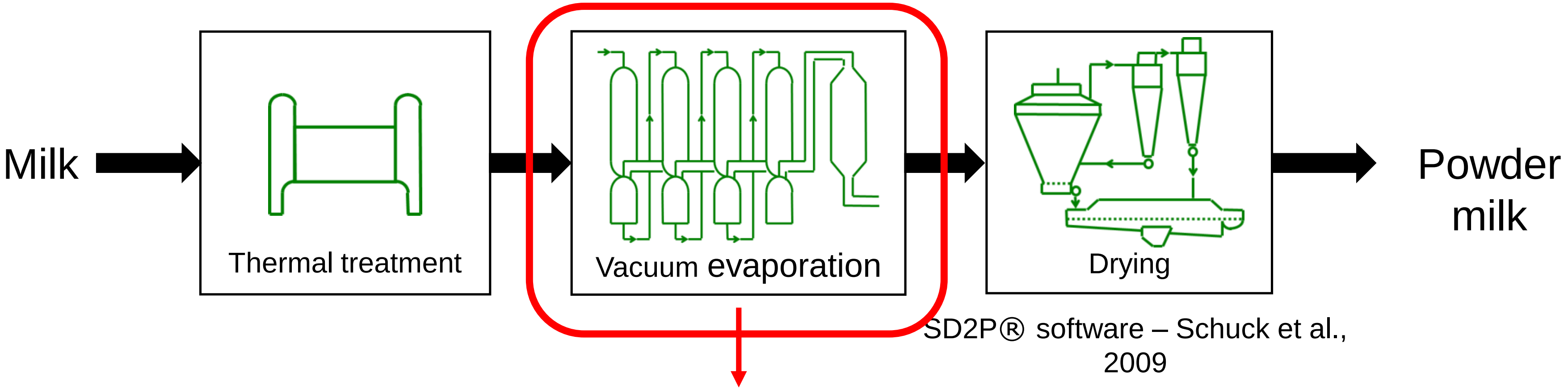
Lack of process models
- Food properties difficult to predict
- Lack of knowledge on the impact of decision variables
- Scarce use of process simulators

Sustainability strategy n° 4 : 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

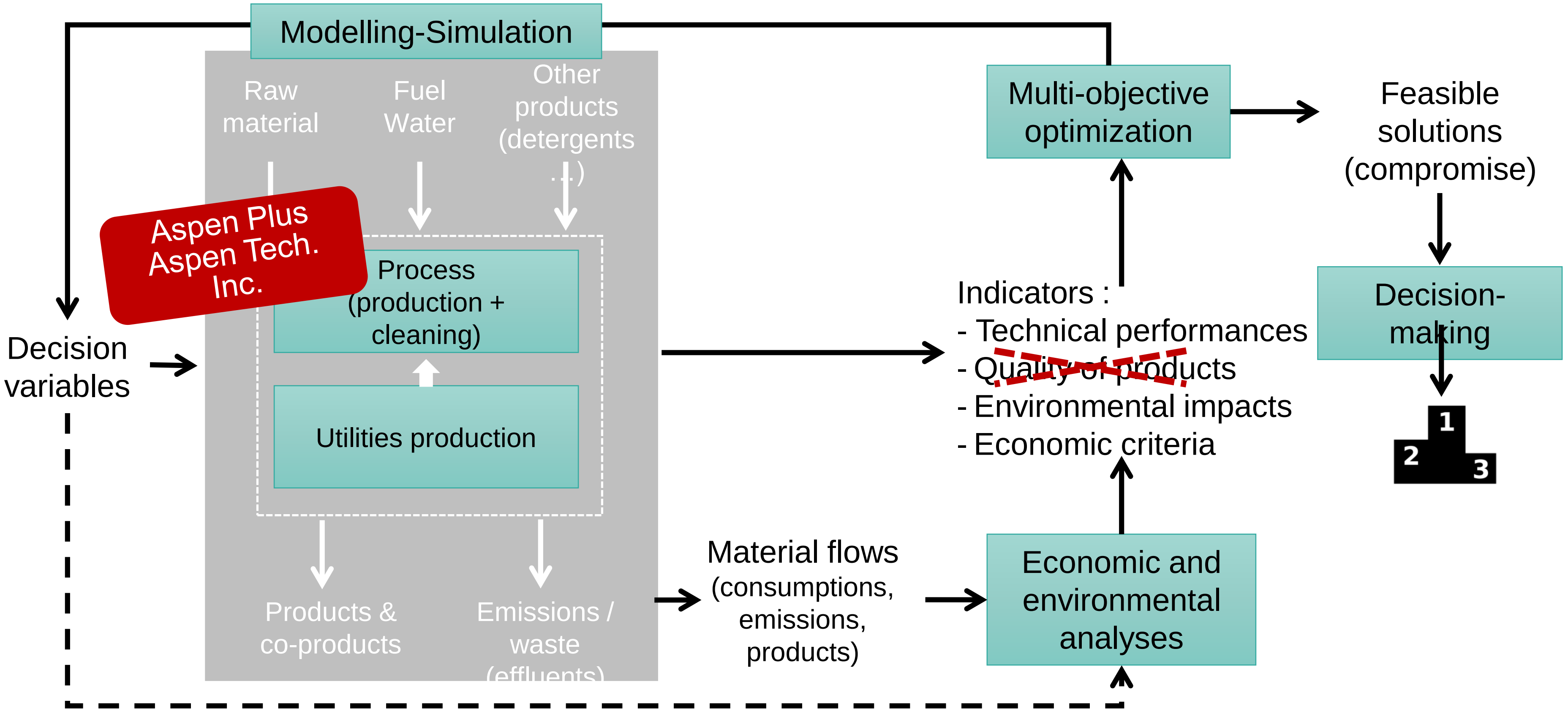
- ❑ > 50% of the energy consumption of the overall concentration and drying process (Jebson, 1991)
- ❑ Various options for evaporator design

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

Sustainability strategy n° 4 : Multi-objective optimization

Case study: evaporation of milk / process simulator

Madoumier et al. 2016

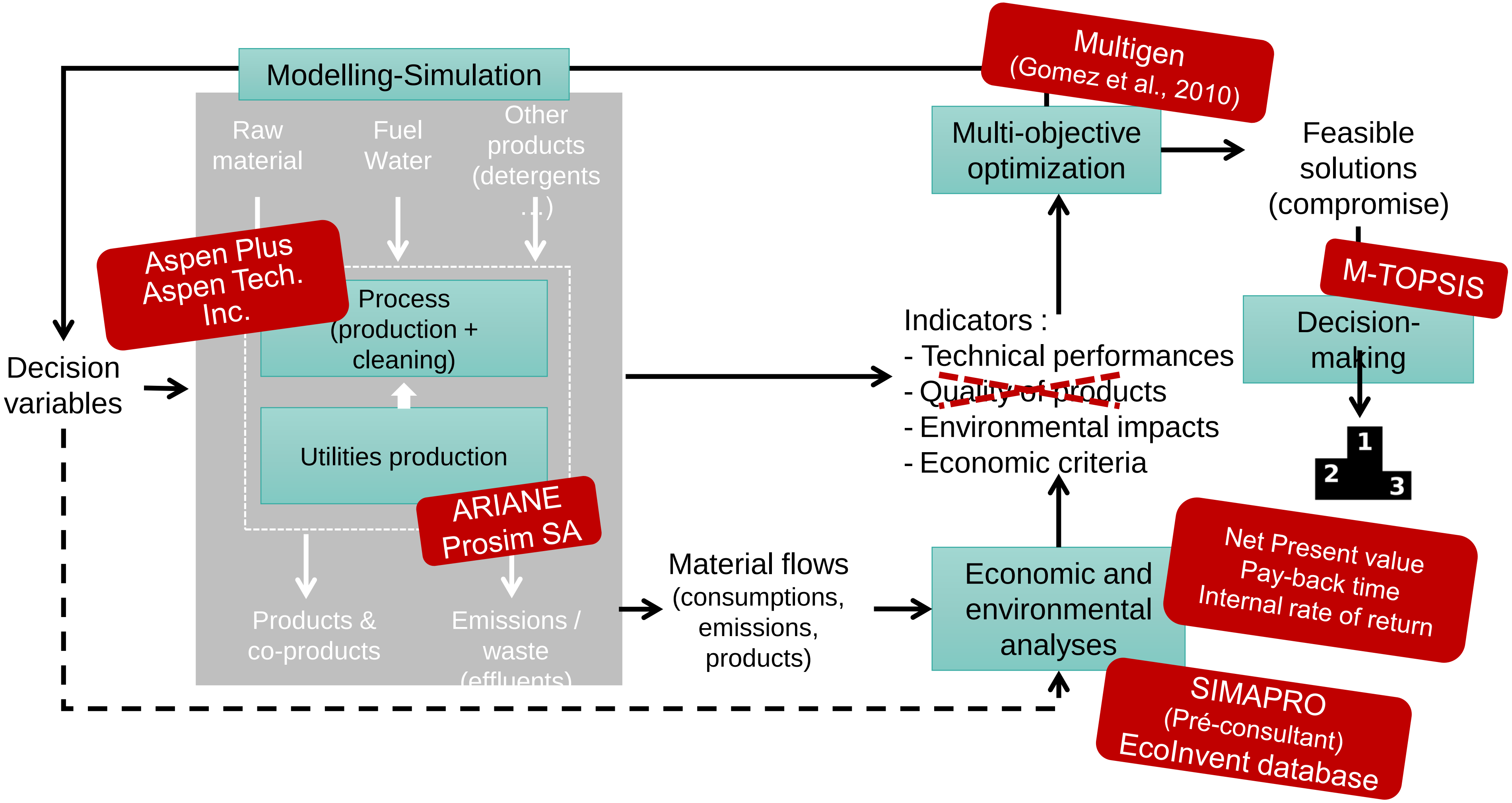


Choice of Aspen Plus

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

Sustainability strategy n° 4 : Multi-objective optimization

Case study: evaporation of milk / process simulator

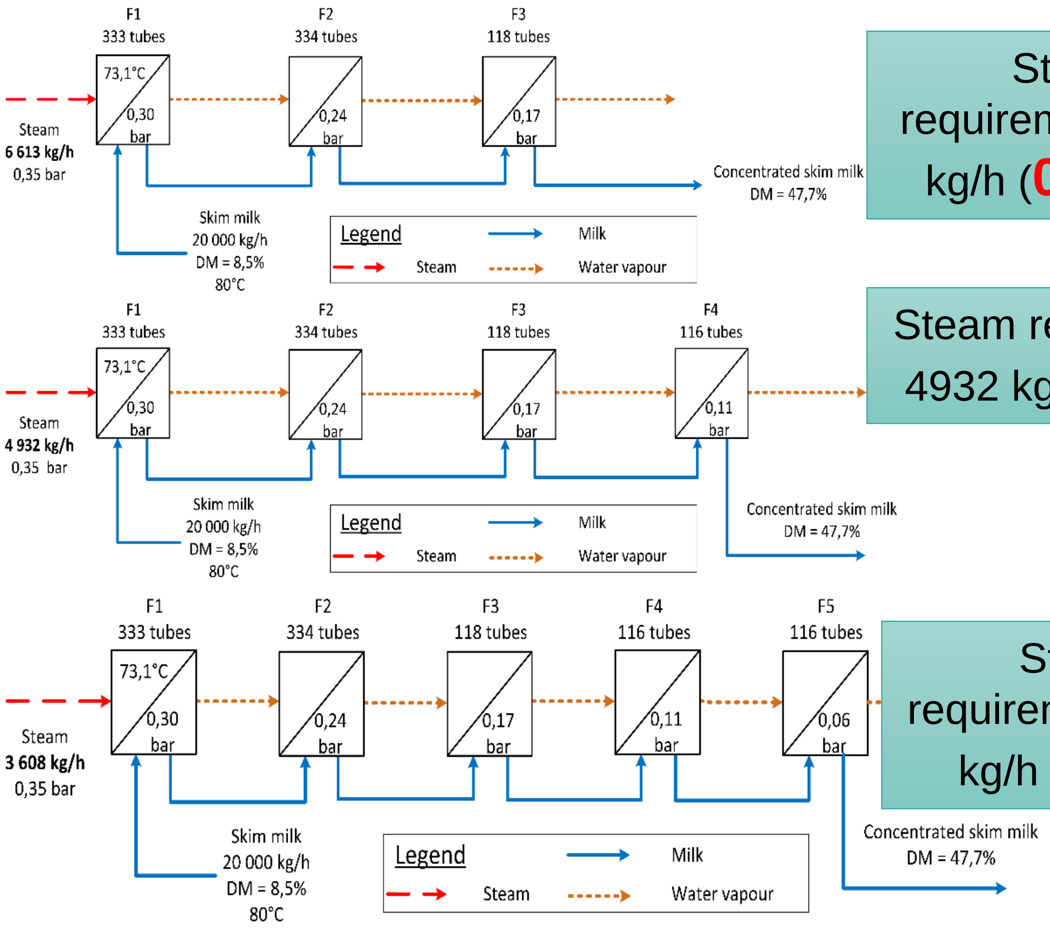


Azzaro-Pantel et al., 2022

Sustainability strategy n° 4 : 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])

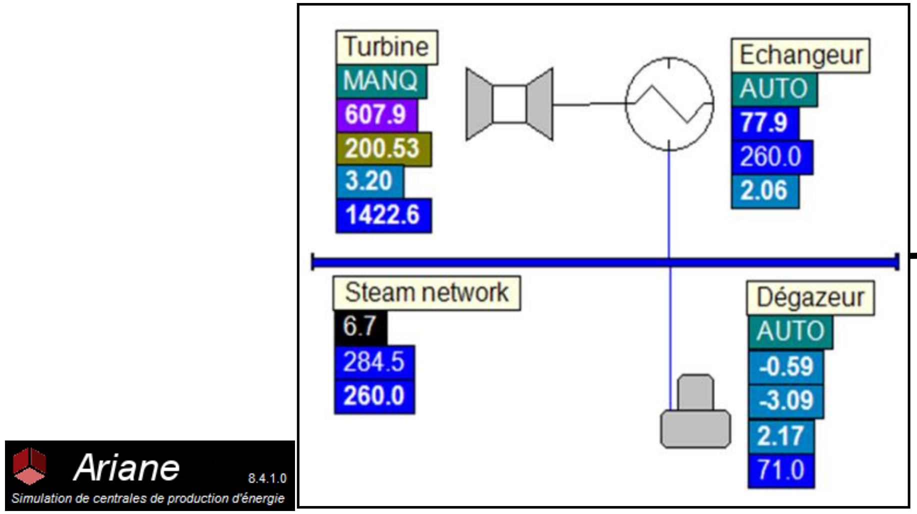
Sustainability strategy n° 4 : Multi-objective optimization

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



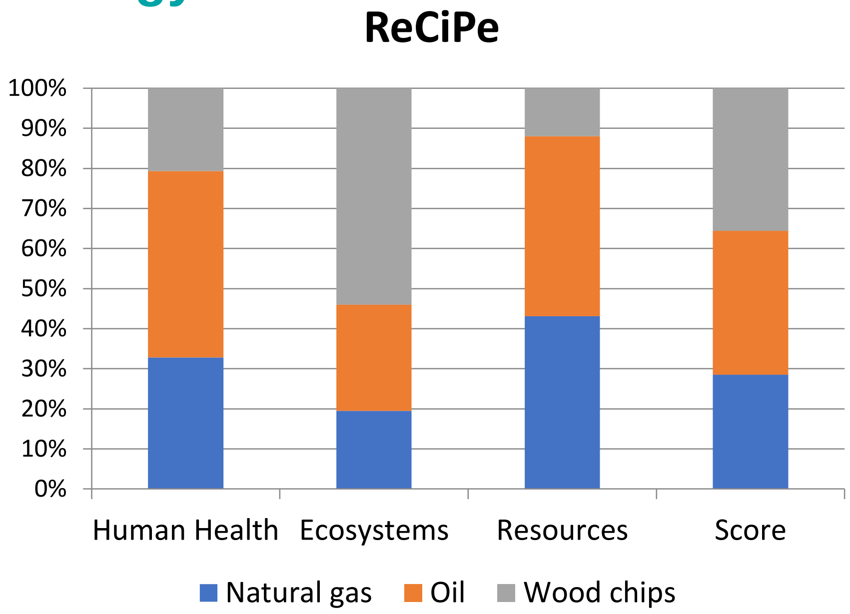
Calculation of utility consumption (water, fuel, etc.), electricity) combustion emissions (carbon dioxide, nitrogen oxides, etc.) according to energy demand of the evaporator → environmental and economic impacts

Sustainability strategy n° 4 : Multi-objective optimization

Case study: evaporation of milk / process simulator

→ Choice of the primary source of energy

Environmental criteria



Economic criteria

	Net Present Value (M€)	Pay-back time (years)	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%)

Sustainability strategy n° 4 : Multi-objective optimization

Case study: evaporation of milk / process simulator

→ Choice of the primary source of energy

Multicriteria analysis (M-TOPSIS)

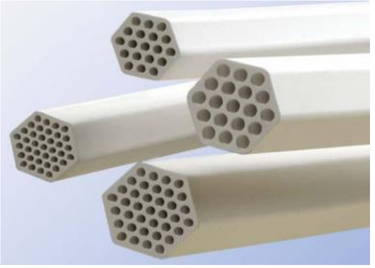
	Combustible		
	Natural gas	Oil	Wood chips
Net Present Value, Single score ReCiPe	1	3	2
3 economic criteria, 3 Endpoint scores ReCiPe	2	3	1

Sustainability strategy n° 4 : Multi-objective optimization

Case study: microfiltration of milk / knowledge integration

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 permeaility gradient

Spiral wound

- ❑ Various options for microfiltration design → conflicting objectives

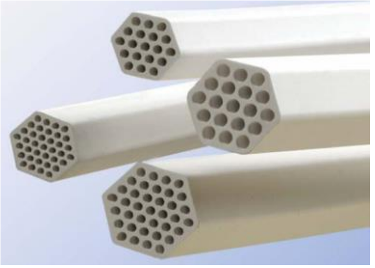
Hobballah et al. Expert Syst. (2018); Belna et al., 2020

Sustainability strategy n° 4 : Multi-objective optimization

Case study: microfiltration of milk / knowledge integration

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 permeaility 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

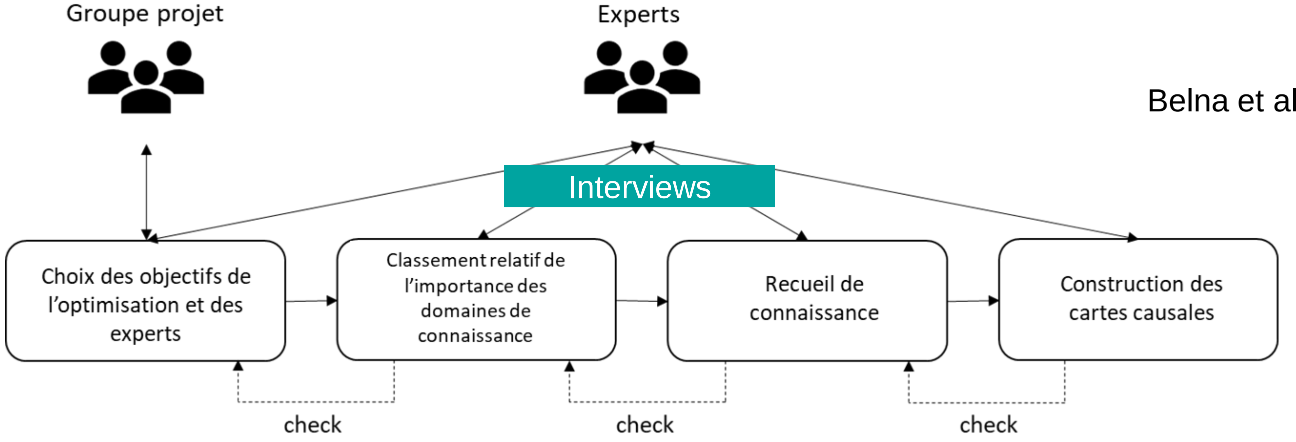
> Use of « Expert knowledge integration » to design microfiltration

Hobballah et al. Expert Syst. (2018); Belna et al., JFE (2020)

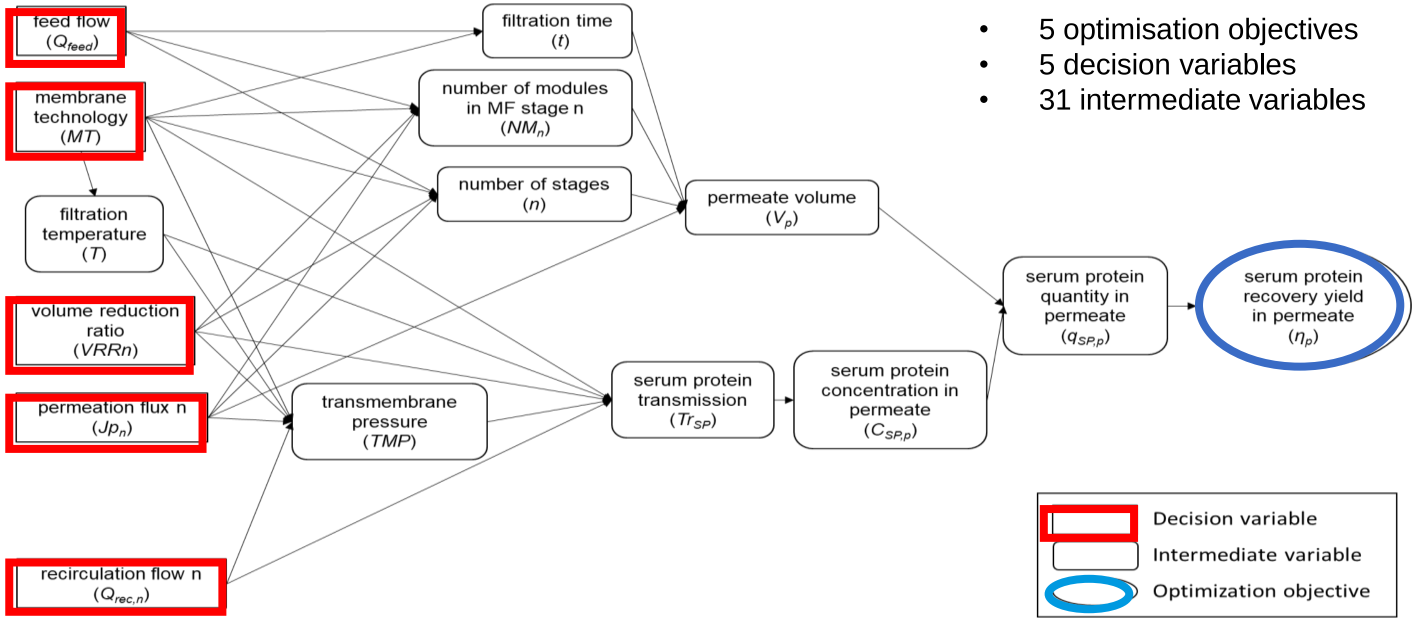
Sustainability strategy n° 4 : Multi-objective optimization

Case study: microfiltration of milk / knowledge integration

Belna et al. JFE, 2020



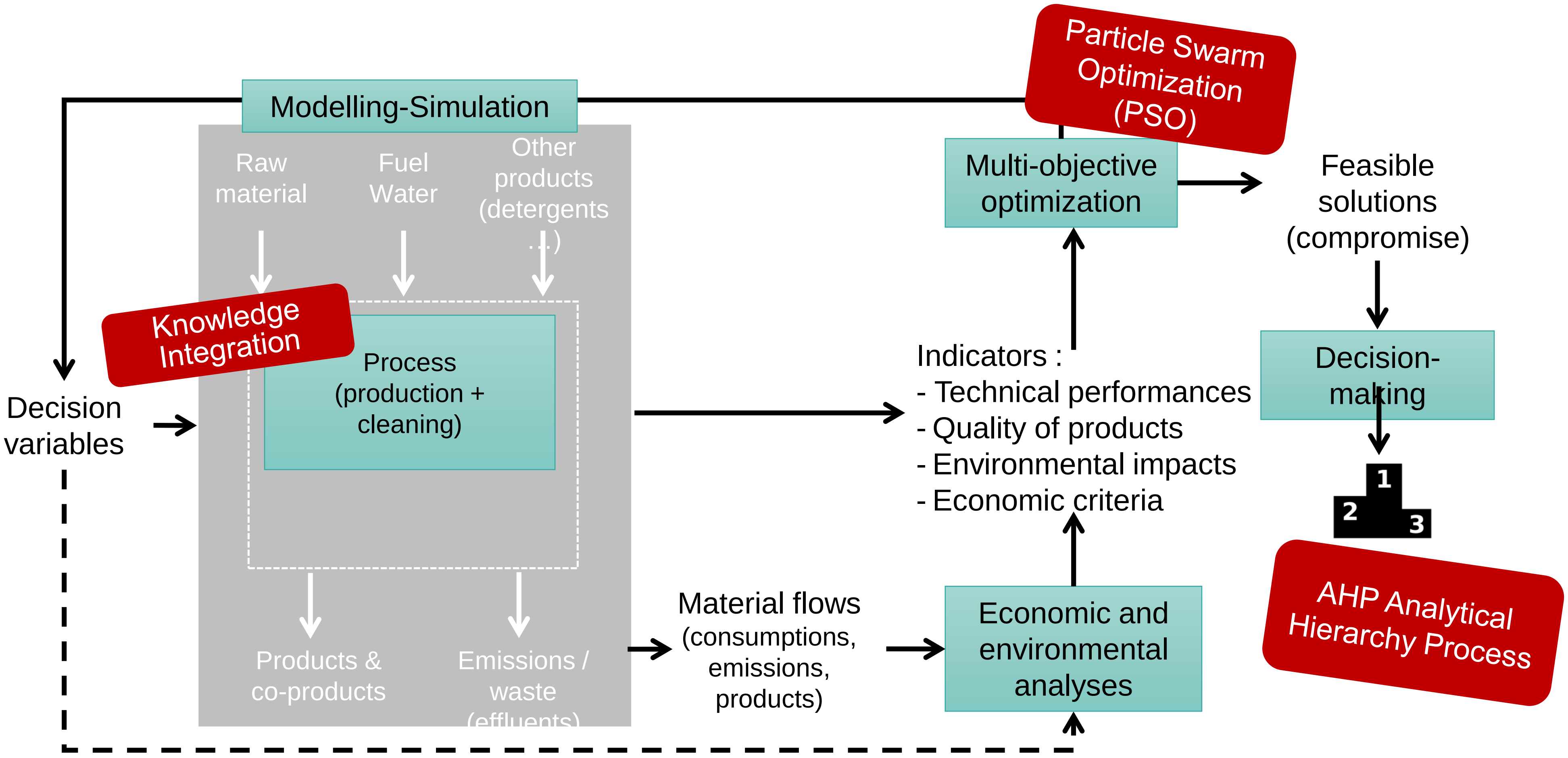
- 5 optimisation objectives
- 5 decision variables
- 31 intermediate variables



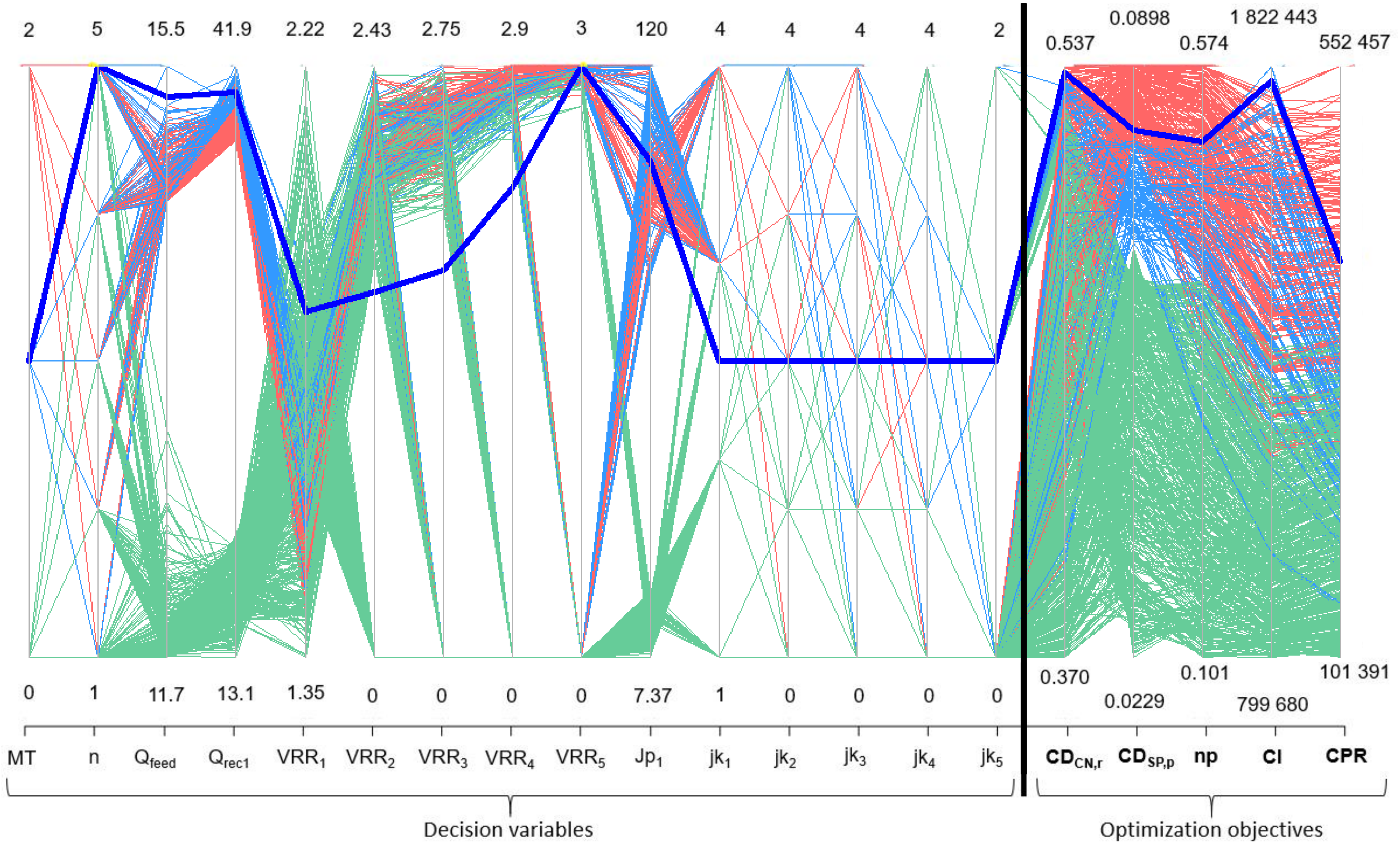
$$\eta_p = \frac{q_{SP,p}}{q_{SP,milk}} = \frac{C_{SP,p}\left(V_{feed} - \left(\frac{V_{feed}}{VRR}\right)\right)\rho_p}{C_{SPmilk} \cdot V_{feed} \cdot \rho_{milk}}$$

Sustainability strategy n° 4 : Multi-objective optimization

Case study: microfiltration of milk / knowledge integration



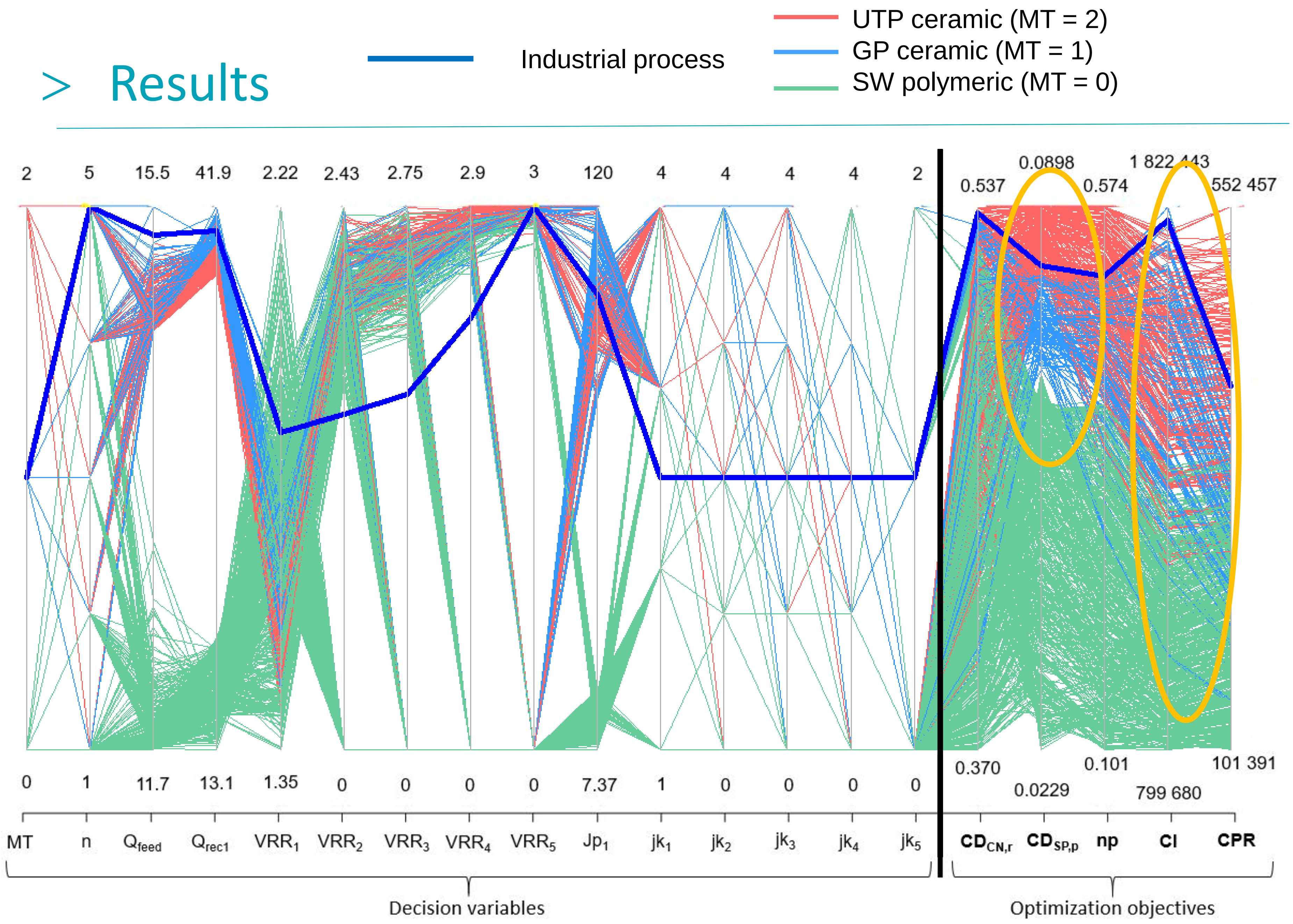
> Results



- Over 1000 Pareto-optimal solutions

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 (€)

> Results



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

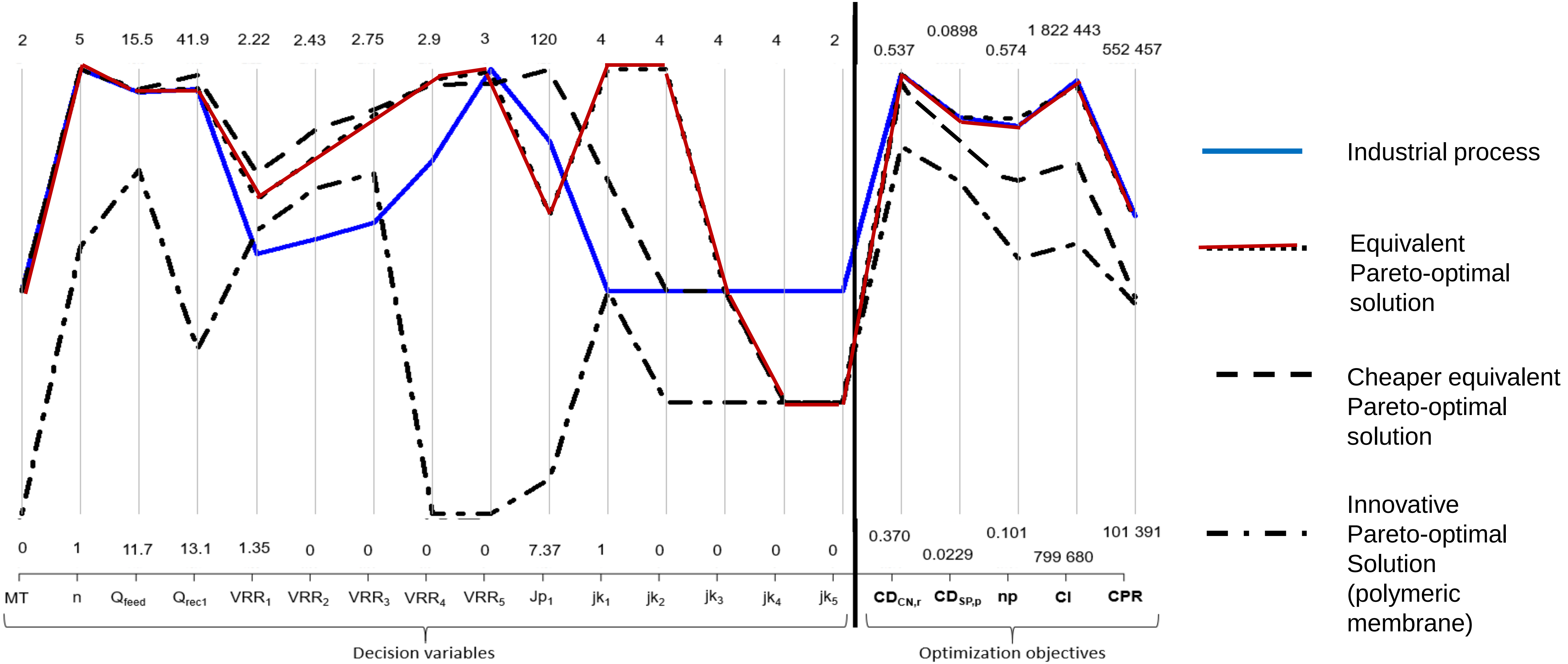
Technical objectives **more efficient**

BUT

More expensive

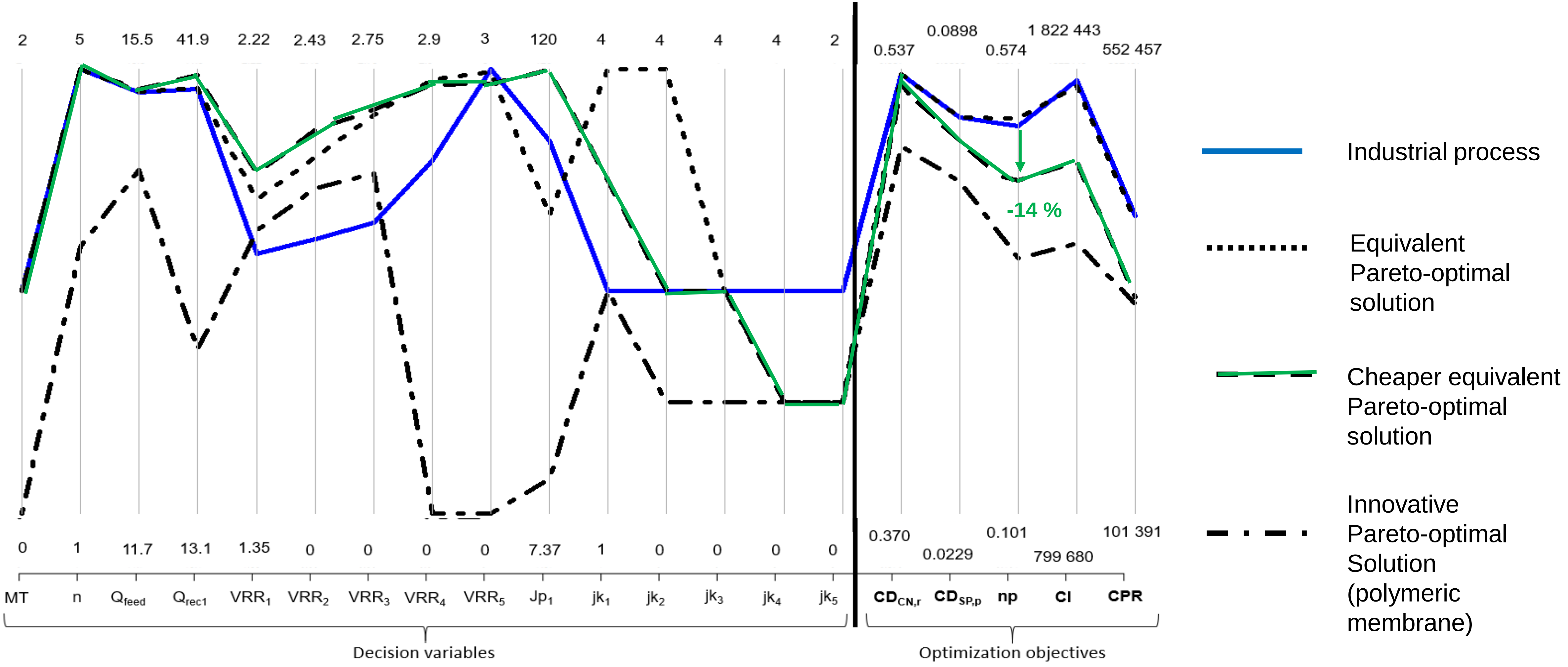
Q_{feed} ($m^3.h^{-1}$) ; Q_{rec1} ($m^3.h^{-1}$) ; Jp_1 ($L.h^{-1}.m^{-2}$) ; CD_{CNr} ($g.kg^{-1}$ DM) ; CD_{SPp} ($g.kg^{-1}$ DM) ; CI (€) ; CPR (€)

> Particular Pareto-optimal solutions analysis



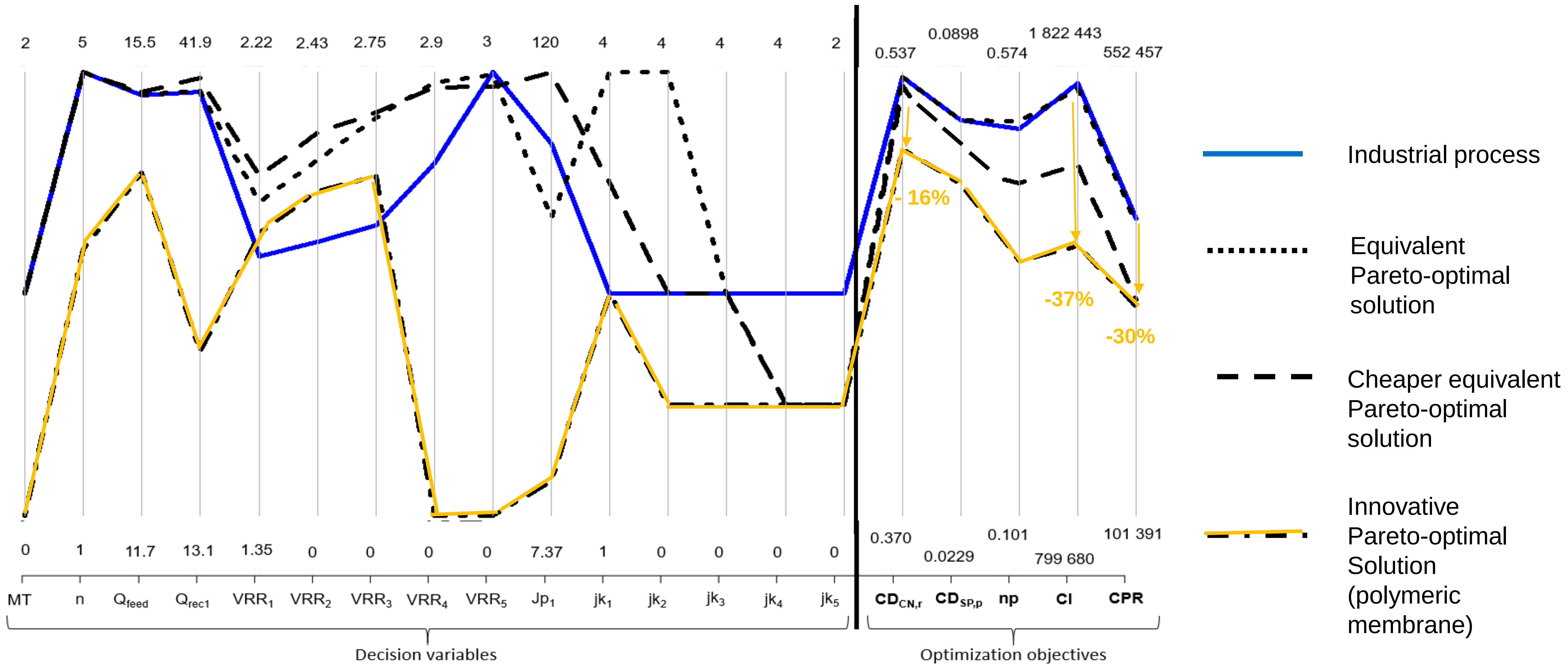
Q_{feed} ($m^3.h^{-1}$) ; Q_{rec1} ($m^3.h^{-1}$) ; Jp_1 ($L.h^{-1}.m^{-2}$) ; CD_{CNr} ($g.kg^{-1}$ DM) ; CD_{SPp} ($g.kg^{-1}$ DM) ; CI (€) ; CPR (€)

> Particular Pareto-optimal solutions analysis



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



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 (€)

Decision

S1  MT = GP ; n=2

S2  MT = UTP ; n=2

S3  MT = UTP ; n=4

Decision = f (preferences of end-users)

> Concluding remarks

Strategies of sustainability adapted to food processing have emerged for < 20 years
→ Different levels of strategies are possible

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

Membrane processes contribute to the sustainability of food processes
Efforts are still needed

- to improve their design and cascade
- to improve cleaning
- to improve the models and predictive approaches which could help develop multi-objective optimisation methods for processes

Thank you for your attention !

And to all contributors …