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ABSTRACT

The food industry urgently needs to design sustainability into its processes. Here we develop a methodological framework for the ecodesign of food processes. The framework combines process flowsheeting (using a process simulation tool) and multiobjective optimization with life-cycle and cost-cycle analysis tools embedded in a multicriteria decision support tool. The framework developed is illustrated by the example of milk evaporation, which is one of the most energy-intensive processes in the dairy industry and has huge potential for optimization. The commercial process simulator was first adapted to modeling milk evaporators. Economic and environmental criteria were then computed from inventories of both the production and cleaning phases, and we went on to apply multiobjective optimization (with a genetic algorithm) and multicriteria decision-making either independently or in combination. The potential of the framework was demonstrated first through analysis of three evaporator design solutions, and second as a support for the strategic choice of a fuel for the purpose of on-site energy production. This work provides a pathway to ecodesigning the entire milk powder production chain.

1. Introduction

Human diets increasingly include industrially-processed food products to meet growing demand for standardized and/or functional food. More than 70% of all agricultural goods currently produced in the European Union (EU) gets transformed into manufactured food products, and this trajectory is set to intensify (EC; Hugues, 2004) as food manufacturing processes increasingly integrate the multiple fractionation, assembly and formulation steps required to propose a vast array of food products with specific nutritional, functional and technological properties. This increasing rate of food processing in addition to the increasing complexity of food manufacturing forces the food industry to address its impact on the environment. The environmental impact of food manufacturing processes is far from negligible, even if the onus is typically more on the upstream stages of field and on-farm food production due to their more direct environmental impact (Davis et al., 2007). In the dairy sector for instance, studies show that membrane-technology milk processing consumes 0.2-11 L of freshwater per liter of processed milk, generating the same amount of wastewater with a pollution load of 0.2–2.5 g biological oxygen demand per liter (Daufin et al., 2001). In addition to its environmental impact, the food indus-

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try is under considerable strain to feed to a fast-growing world population (9.7 billion people by 2050 under the United Nations (UN) medium-variant projection) (United-Nations, 2019). The need for safer, affordable, nutrient-rich food produced under environmentally-friendly conditions creates a need for approaches to support ecodesigned food manufacturing processes (Esnouf et al., 2013).

There are basically three main approaches for ecodesigning food manufacturing processes. The first food-process ecodesign approach, which is not yet widely implemented at the industrial level, involves comparative environmental assessment of either different processes or different scenarios for a particular process that is then iteratively improved. This approach typically employs life cycle assessment (LCA) to single out the most environment-negative processes and unit operations to help guide process engineers towards an improved design. The major advantage of this iterative-improvement ecodesign approach is that it is fairly simple and readily implementable, and has thus found a number of applications (Bosworth et al., 2000; Dvarioniene et al., 2012; Prasad et al., 2004; Sharma et al., 2012; Westergaard, 2004).However, this LCA-based approach quickly becomes hugely complex when the processes compared or suggested changes to the same process entail changes in the quality and/or end-use properties of the final product (for instance, reducing the temperature of a heat treatment may change the degree of denaturation of the product and thus its final end-use properties) and therefore in the ‘functional unit’, which is the core basis for comparison in LCA. The main disadvantage is that it limits the scope for optimization strategies and decision-making methods, which hinders attempts to find a global optimum of the manufacturing process from among different partially-conflicting indicators and fails to provide the operator with appropriate support.

The second approach is based on minimizing material flows (particularly energy and water) within the process, either via modifications to operating conditions (e.g. temperature reduction) or via a redistribution or reuse of the flows within the process (e.g. heat transfer fluid) based on specific methods such as pinch analysis or exergy analysis (Walmsley et al., 2013, 2016). Such improvements normally have a direct effect in terms of reducing both environmental impact and costs, but the approach also has to take into account the potential changes to the product caused by the suggested modifications. Incomplete data is effectively the major limitation to this ecodesign approach. In many cases, the data needed is either not even measured on-site or cannot be published due to proprietary or trade-secret reasons. Reliable data obtained at pilot scale is not necessarily representative at industrial scale and can therefore only be used if the polite-scale data is shown to correlate industrial scale.

The third and most ambitious systemic approach is the far-reaching integral simulation-optimization ecodesign approach. Process design is often basically a compromise between different technological, economic and environmental objectives. Process design can be improved by minimizing key process-related quantities, i.e. inputs (water, energy and chemicals), environmental impacts and the related costs, while maximizing productivity and product properties. The manufacturer typically sees these objectives as single constraints that are iteratively added and, therefore, ultimately perceived as reducing the degrees of freedom and thus tightly restricting process control and design. Only the kind of multi-objective design proposed by this third approach can integrate the notion of compromise, consider major technological innovations by co-optimizing conflicting objectives, and tease out the optimal solutions. This approach, combining process modeling, simulation and optimization, provides a sound platform for the ecodesign of manufacturing food processes (Azapagic et al., 2011; Lam et al., 2011).

For developing the simulation-optimization ecodesign approach, the benefit of using computer-aided process engineering tools has long been recognized in the chemical and petroleum industries. However their use is not yet systematic in the development of food processes. A major limitation of the development and use of computer-aided process engineering tools in food processes is attributed to the complexity of food products and their intrinsic thermodynamic properties.

The objective of this work is to develop a framework for ecodesigning food processes using multicriteria assessment

The environmental energy consumption of milk powder is mainly due to the consumption of the dryer. Several works have already been conducted to reduce the energy consumption of spray dryers (see, for example, Schuck et al., 2015). However, comparatively little work has been carried out on reducing the energy consumption of evaporators, which are used to concentrate the milk before spray drying. This operation is therefore targeted here. It should be emphasized that the primary objective of this work is not to optimize the evaporation process applied to milk, but to develop a framework for the ecodesign of food processes using a multicriteria assessment and to demonstrate its potentiality when applied to milk concentration processes. The choice of process is therefore not significant for this paper, which is more methodologically oriented.

The concentration step using evaporation will serve as a validation case for the methodology proposed. Milk powder production is one of the most energy-intensive processes in the dairy industry, and efforts are still needed to reduce the energy consumption of falling film evaporators that are used to concentrate the milk prior to spray-drying. The evaporator is modeled using a process flowsheeting simulator with the thermodynamic properties of concentrated milk determined in previous work (Madoumier et al., 2015).

The potential of this process flowsheeting–multicriteria decision-making framework is demonstrated first through the analysis of three design solutions for an evaporator, and second as a support for the strategic choice of a fuel for the purpose of on-site energy production.

2. Material and methods

2.1. *The evaporator: a key process in the ecodesign framework*

A reference evaporator corresponding to an existing industrial installation is used in this work to develop and validate the modeling–simulation tool for the ecodesign methodological framework. This reference process is composed of a four-effect falling-film tubular evaporator that can process 19,500 kg of milk per hour. The process scheme and its allied operating conditions were provided by the user and the equipment supplier involved in the latest modifications of the installation (sources kept confidential).

Fig. 1 shows the process studied. A total of five preheaters (RF0 to RF4) bring the milk (8 °C) to a temperature close to pasteurization temperature (67.1 °C). The preheaters are fed

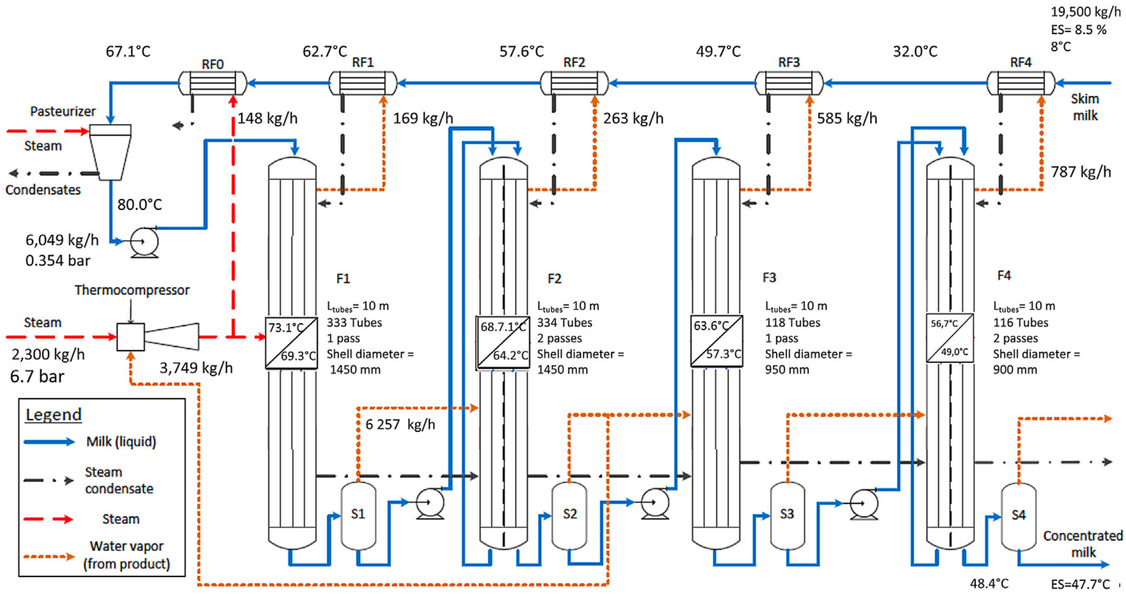

Fig. 1 – Process flow diagram and operating conditions of the industrial evaporator of reference for this study (F: effect; RF: preheater; S: separator).

by water vapor from the effects (F) of the evaporator or directly from the thermocompressor. The cream separator (centrifuge separator) is not shown in the figure but is part of the production-route chain. Pasteurization is performed with a steam infusion system that brings steam directly into contact with the milk on which it condenses, thus bringing it to the setpoint pasteurization temperature (80 °C). The milk is then exposed to a light vacuum to extract the water added to the milk by steam condensation. The thermocompressor powers the first effect (Fl) with steam, which is obtained by mixing water vapors from the second effect (F2) and steam from the power plant. The steam that powers the thermocompressor is at a pressure of 6.7 bar and a flow rate of 2300 kg/h, and the thermocompressor produces steam at 0.354 bar to feed the evaporator.

The four effects F1 to F4, which alternately use one or two product run-throughs, concentrate the milk from 8.5% to 47.7% (Fig. 1). The flowrate of treated milk is 19,500 kg/h. The modeling step was validated by measuring the temperature and dry matter content of the concentrate at the evaporator outlet. For the milk concentration configuration described here, the validation only used the heat capacity and boiling delay models. Boiling temperature is a known factor in all four effects and can thus serve to deduce the pressure imposed.

The cleaning parameters used are considered as fixed and are similar to those previously used by Madoumier et al. (2020): pre-rinse with water (ambient temperature, 20 min); alkaline cleaning with 1.5% caustic soda (75 °C, 30 min); intermediate rinse with water (ambient temperature, 15 min); acid cleaning with 2% nitric acid (60 °C, 30 min); a final rinse with water (ambient temperature, 15 min).

2.2. *The ecodesign framework based on multicriteria assessment*

Fig. 2 gives an overview of the methodological framework applied to evaporative concentration of skim milk (the drying stage is not considered in this study). The ecodesign methodology proposed in this study integrates mathematical modeling of the evaporative concentration process coupled with an environmental and techno-economic assessment, which is embedded in an outer multiobjective optimization loop followed by a decision support method. Process modeling in the production and cleaning phases uses mass and energy balances to inventory the inputs and outputs of the system considered.

It must be emphasized at this level that the principles of the framework development are not dependent of the tools used. A systematic, generic approach for sustainability assessment and design selection was previously proposed through integrating economic and environmental indicators (Morales-Mendoza et al., 2018). It is based on a methodological framework for process ecodesign, coupling flowsheeting simulators both for production and energy processes with a life cycle assessment module that generalizes and automates the evaluation of the environmental criteria. The guidelines that were previously developed for chemical processes were adopted here for food processes. Yet the application of the framework was conducted with specific tools for the implementation phase.

For the production phase, the modeling of the dairy evaporator process was adapted from commercial design and flowsheeting packages initially developed for chemical processes (Madoumier et al., 2020). For the cleaning phase, the Gallot-Lavallée cleaning kinetics model was selected to predict cleaning duration and thus process performance indicators as a function of cleaning parameters (alkali cleaning temperature, concentration and flow rate (Gallot-Lavallee et al., 1984). The choice of the Gallot-Lavallée cleaning models was previously discussed by Madoumier et al. (2020).

Cleaning phase was linked to production phase using different hypothetical fouling kinetics laws that can predict fouling surface density as a function of production duration. A key factor in the methodology implemented here is that it uses the ARIANE^{TM} decision support tool purpose-engineered for process management decisions in plants that produce utility energy (steam, electricity, hot water, etc.), which is bundled with the Plessala^{TM} module developed by ProSim S.A. (2005). ARIANE^{TM} is used here both to compute the primary energy requirements of the process and to quantify the pollutant emissions generated by energy production. Note that a product quality indicator (in italics Fig. 2) was not consid-

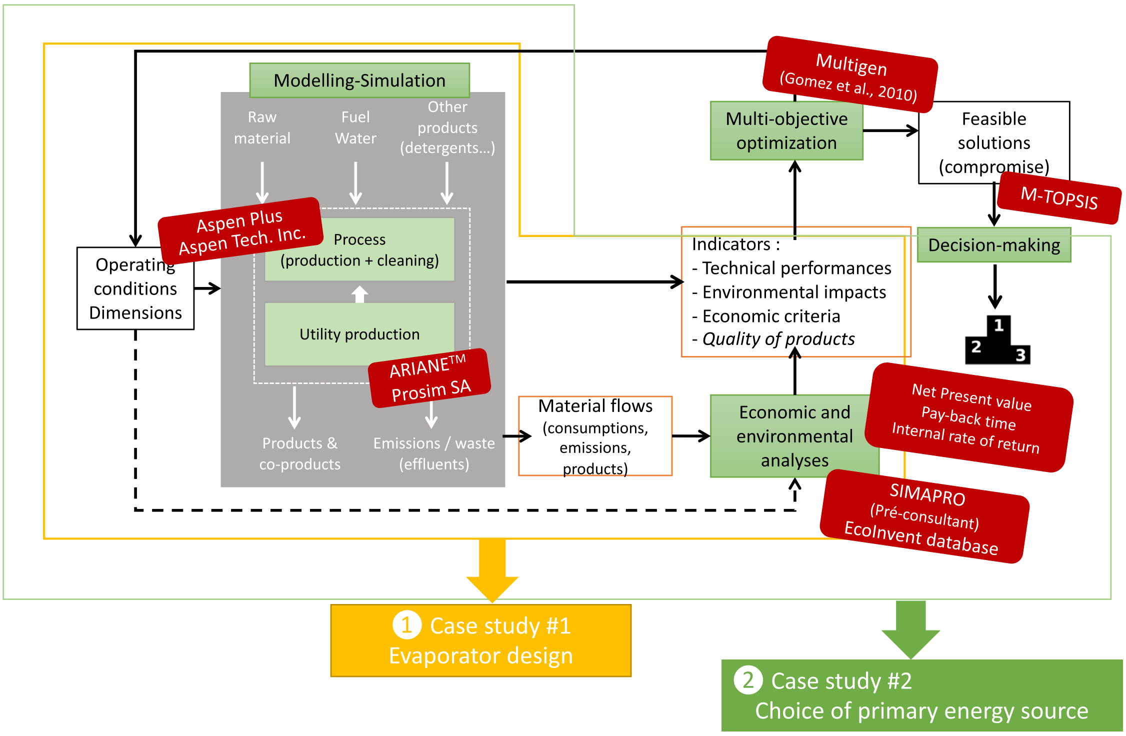

Fig. 2 – Ecodesign framework applied to an evaporator.

ered here but could readily be implemented in our generic framework. Pareto curves are used to illustrate the trade-off between economic and environmental objectives, and a synthetic evaluation method based on multicriteria decision-making (MCDM) is then used to help decide between the various alternatives that can be generated after this step. The work reported here does not specifically exploit the whole set of potential pathways in this framework (which have been published elsewhere, as listed below), but it is useful to give a concise picture of the various components in the framework and how they integrate together.

2.2.1. *Process modelling*

The evaporation process was simulated using Aspen Plus simulation software (Aspen Technology, 2011), as it features a large library of unit operation models, powerful capabilities for integrating and modeling components that are not included in its built-in database, and the interoperability needed to facilitate coupling with optimization procedures (You et al., 2012). This is a particularly attractive asset for further use of the simulator in ecodesign approaches that account for process performance. The physical property system in the process simulator first requires the milk to be identified. Milk cannot be described as a standard chemical compound as it is a complex mixture of more than 2000 components. To address this issue, several works (Bon et al., 2010; Madoumier et al., 2015; Munir et al., 2016) modeled milk in Aspen Plus as a mixture of five conventional components: cow water, i.e. the water vapor separated from the milk (which has properties that are very close to pure water), milk fat, proteins, carbohydrates (mostly lactose), and ash (minerals). From a methodological viewpoint, we scanned the literature to select a set of thermodynamic models that are valid for cow's milk (or assumed valid for cow's milk when milk source was unspecified). The different models describing the same property were then compared against each other and against experimental data within their validity ranges. For that purpose, we computed each specific property using these published models at three or four different levels of dry matter content and in a temperature range consistent with the evaporation process. The significant properties of milk (heat capacity, boiling-point elevation, thermal conductivity, density, viscosity, surface tension) were then modeled as a function of temperature, dry matter content and composition, and these thermodynamic models were selected to compute the physical-chemical properties of individual components (or pseudo-components) and mixtures involved in the evaporation process. The unit operations involved in the industrial evaporation process were modeled using the built-in blocks in Aspen Plus, as explained in Madoumier et al. (2015) (Fig. 3). The pre-heaters and the pasteurizer of the industrial plant were modeled with 'Heater' blocks, which perform heat and mass balances on a stream under varying pressure or temperature, or exchanging heat. The two-pass multiple-effect evaporator was modeled using several *HeatX* blocks corresponding to the number of passes in each evaporator effect.

Two-pass effects were thus modeled by two *HeatX* blocks in order to factor the influence of wetting rate of the tubes on the transfer coefficient. It was also necessary to divide the steam stream that feeds each effect (steam or water vapor) into as many streams as product passes in the effect, so that each pass receives equal thermal power. The vapour—liquid separator associated with each effect is modeled with a *Flash2*block. A user model was required to model the evaporators in Aspen Plus as the geometry of the tubular evaporators employed in this industrial process do not have a geometry that matches the TEMA (Tubular Exchanger Manufacturers Association) standards implemented by the *HeatX* block. Thus, instead of using the built-in heat-exchanger model of the *HeatX* block, we developed a user routine that accounts for the simple geometry of the falling-film tubular evaporators. The routine also integrates a specific heat exchange coefficient model, as the heat exchange model available in Aspen Plus is not satisfactory for this milk evaporation case. This 'user model' approach was similar to that adopted in (Ribeiro and Andrade, 2003) who

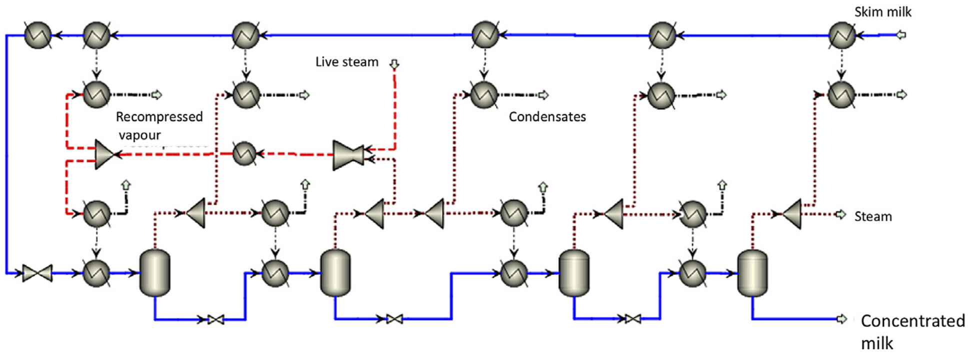

Fig. 3 – Flowsheet of the industrial evaporator using Aspen Plus.

Table 1 – Comparison between experimental values and simulation for the concentrate properties with Aspen Plus.

Process	Concentrate properties					
	Dry matter (mass%)			Temperature, °C		
	Exp. data	Simulation	Deviation	Exp. data	Simulation	Deviation
Industrial evaporator	47.7	48.1	+ 1%	49.0	49.1	≦1%
STLO Evaporator (run 15% → 52%)	52.0%	48.0%	−9.0%	60.0	61.3	+2%

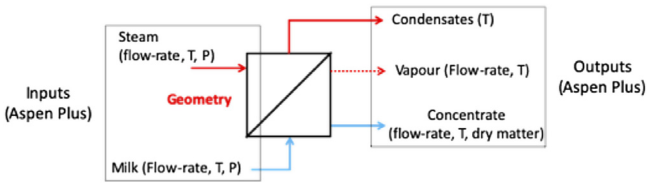

Fig. 4 – Input and output of the Aspen model (Industrial evaporator and Milk Platform, STLO INRA).

developed a rigorous mathematical model for a climbing-and-falling film evaporator. The heat transfer coefficient model proposed by Bouman et al. (1993) was demonstrated to be the most efficient model for industrial evaporators and was adopted in the Aspen model (see Madoumier, 2016 for more information). The inputs and outputs of the Aspen model are consistent with the experimental data presented in Fig. 4 and Table 1. Table 1 shows that both the temperature and dry matter of the milk concentrates are well predicted by the process model, since a with less than 1% deviation between experimental values and simulation results in the case of the industrial evaporator. In the case of the STLO evaporator however, simulation results and experimental values differ more significantly. Since this evaporator is a pilot equipment (with a flow rate of 50–70 kg/h), it has been shown that the model developed in Bouman et al. (1993) for the estimation of heat transfer coefficient is not well adapted to this process scale. A discussion on the selection of the heat transfer coefficient has been proposed in Madoumier et al. (2015).

2.2.2. *Computation of inventories from energy generation plants*

The power generation plant that supplies power to the steam network and provides the energy necessary for the process unit operations (evaporator, pasteurizer, heating cleaning solutions, etc.) generates environmental impacts. To integrate the primary energy consumption and emissions induced by energy demand into the overall ecodesign of the process, the energy production inventories are calculated using a purpose-dedicated simulator (ARIANE™, ProSim S.A). The ARIANE™ simulation tool used in previous research (see Morales-Mendoza, 2013; Ouattara et al., 2012 for examples of uses) was used here to calculate both the utility consumption (water, fuel, electricity, etc.) and combustion emissions (carbon dioxide, nitrogen oxides, etc.) of a power plant according to the energy demand of the studied process. ARIANE™ was selected for two main reasons. First, it offers possibilities for specifying each unit of energy-producing equipment (a boiler or cogeneration turbine, for example) with its specific operating parameters (thermal efficiency, pressure, etc.) within the plant, and for simulating the supply of different steam or hot water systems used in the process. Second, the interoperability between ARIANE™ and other software tools makes it possible to extract the simulation results (fuel consumption, component flows) to a digital support (typically an Excel spreadsheet) so that all the items in the power plant (boiler, network, fuel, etc.) are readily accessible. In order to calculate utility consumption, we modeled a steam power plant with a mono-fuel boiler in ARIANE™. This steam power plant model is based on current representations of steam generation systems (Jiménez-González and Constable, 2011). The validation of ARIANE™ for steam generation was presented in Madoumier et al. (2013). In detail, the plant energy model (Fig. 5) includes a single-fuel boiler model, a deaerator, and a steam network that feeds the process. The deaerator supplies demineralized water and/or recycled steam condensate to the boiler to feed steam production. This energy generation plant model makes it possible to predict fuel consumption of the boiler as a function of the specified steam demand and the selected fuel source. The selected boiler is assumed to be flexible enough to adapt to different types of fuel, and the equipment is adapted to the characteristics of each fuel (burner, pressurization, supply system, and so on). The power supply for the process is assumed to be provided by the national power grid.

In order to calculate the combustion emissions of the power plant, ARIANE™ calculates the composition of the flue gas (characterized by 8 compounds: CO_2, H_2O, O_2, N_2, CO, NO_X, SO_2, dust) with a combustion reaction model of the primary energy source integrated in the simulator. It calculates also the flow rates of these compounds, obtained by simulation in ARIANE, which allow to calculate the inventory of direct

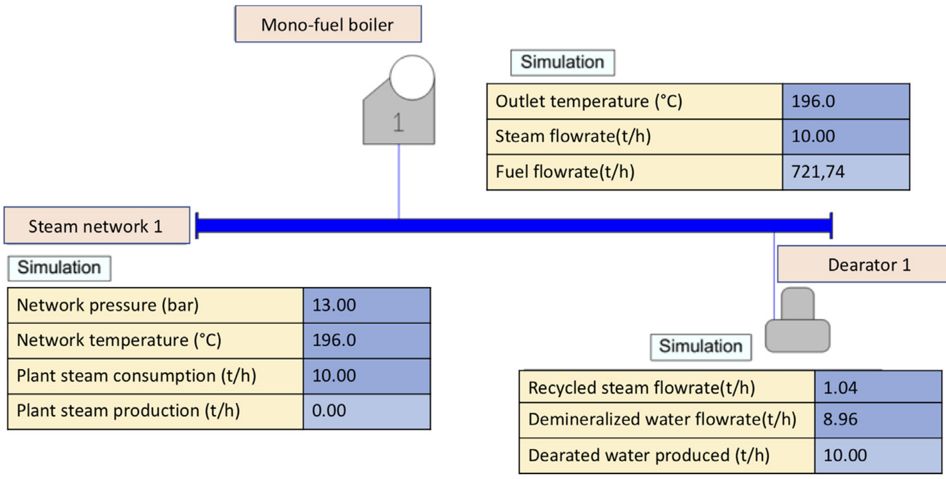

Fig. 5 – Process flow diagram for the mono-fuel boiler modeled in ARIANE^{TM}.

emissions from energy production. As the composition of the emissions depends on the choice of both fuel and energy-producing equipment, ARIANE^{TM} requires several parameters to be specified as inputs, NO_X a ratio of the amount of carbon monoxide emitted per amount of CO_2 (CO/CO_2), and a dust emission factor, to enable the calculation of flue gas composition.

These parameters can be obtained from the literature or through direct on-site surveys. In this study, wood pellets were added in ARIANE^{TM} as a representative fuel for biomass use. The database of physical–chemical properties of wood pellet fuel (in complement to heavy fuel oil and natural gas already included in ARIANE^{TM}) was also added, together with the combustion reaction model needed to determine its flue gas composition. The ARIANE^{TM} simulator is thus integrated into the methodological framework in order to calculate an accurate inventory of direct emissions generated by energy production and evaluate its contribution to environmental impacts.

2.2.3. *Environmental impact assessment*

Life cycle assessment (LCA) was used to estimate the environmental impacts of the process. The system boundary used for the LCA was gate-to-gate, focusing on milk transformation without consideration of its on-farm impacts. The effective contribution of both the production and the cleaning steps is considered following the guidelines presented in Gésan-Guiziou et al. (2019).

The environmental impact associated with electricity consumption by the designed equipment has not been considered since it was integrated into process design and operation. LCA is typically performed using a functional unit that refers to the output/product of a process or a technology. However, as the objective of this study was not to estimate the environmental impact of the products but to examine the environmental impact of the process, we calculated the life-cycle impacts of the whole process. The functional unit was then estimated on input product (as done, for instance, by Gésan-Guiziou et al. (2019) based on 1 kg of milk at the evaporator input.

The LCA study requires a full life cycle inventory (LCI) to characterize the impacts. However, although process simulation can inventory direct emissions from the studied system and its indirect emissions due to energy production, it cannot inventory indirect emissions due to raw material consumption, water pre-treatment and wastewater treatment. It is

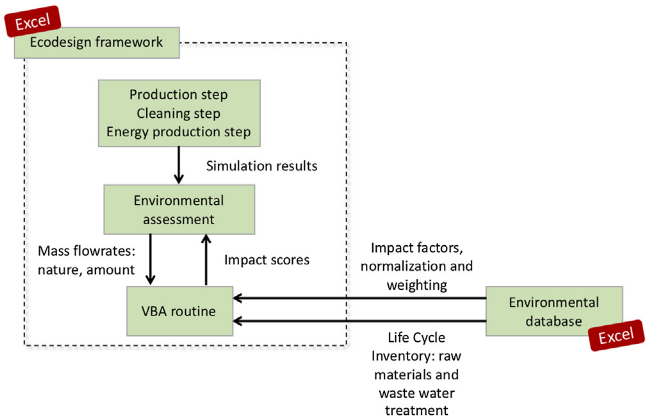

Fig. 6 – Environmental component of the ecodesign framework.

therefore necessary to extract information from the EcoInvent database proposed in the SimaPro software (SimaPro 8.0, http://simapro.com/, PRéConsultants) to estimate the full inventory of the system's indirect emissions as comprehensively as possible. The LCIs available in the environmental database of this work are listed in A.2. SimaPro was also used to extract data on pollutants emitted by energy production and characterize the allied damage factors. For consumption of raw materials and utility power (fuel, water, and so on), the midpoint and endpoint scores were first calculated in SimaPro and then extracted to perform a direct calculation without treatment of all the substances in each LCI. The normalization and weighting factors were also extracted from SimaPro in order to build a database in Excel. The rationale for this choice was that we needed to establish a direct link between SimaPro and the methodological framework for optimization (Morales-Mendoza, 2013; Ouattara, 2011).

The emission and consumption flows are computed from the various simulations (production, cleaning, energy production) and then extracted via a VBA language routine from a database of the LCIs and the corresponding impact factors according to the selected life cycle impact assessment method. The basic principle of the environmental component of the ecodesign framework is presented Fig. 6. We purposely selected two life cycle impact assessment methods, i.e. Impact 2002+ (Jolliet et al., 2003) and ReCiPe (Goedkoop et al., 2013) on the rationale that they are complementary. Impact 2002+ is a combined midpoint and damage approach using both

Eco-Indicator 99 and CML methods, including the impact category of 'non-renewable energy' which is particularly pointful for our study due to the high energy consumption of the milk evaporation process. ReCiPe is a recent comprehensive impact assessment method that includes certain impact categories that are not addressed in Impact 2002+, such as water depletion. ReCiPe uses three different scenarios for damage characterization (i.e. normalization and weighting of scores): egalitarian, which considers long-term impact (500-year timeframe), individualist, which considers short-term impact (20-year timeframe), and hierarchist, which is designed to find a balance between the first two scenarios (100-year timeframe). Here, the normalization value and damage score weighting factors were chosen for the 'hierarchist' perspective, as this scenario is viewed as a consensus model that offers a good balance between short- and long-term perspectives. For this scenario, we chose the normalization factors for Europe as recommended by Goedkoop et al. (2013). The major difference between Impact 2002+ and ReCiPe is the separation of climate change impact of the other endpoint indicator categories, which gives a total of four damage categories. These scores can simply be summed together to give a single environmental impact score.

2.2.4. *Economic impact assessment*

The economic component of the ecodesign framework for this milk evaporation process is evaluated here using several classical indicators of profitability (Fig. 7): net present value (NPV), discounted payback period (DPB) defined as the time at which NPV equals zero, and internal rate of return (IRR), i.e. the interest rate value at which NPV is equal to zero. These indicators are based on the cost to operate the process, the potential revenues from the process, and cost of equipment investment. The economic criteria only include the cost associated with evaporation and cleaning. Calculations of expenditure and revenue require an estimate of the costs of the various inputs (raw materials, utilities, etc.) and wastewater treatment, as well as the selling price of the final product. These prices are listed in an economic database purpose-built for this study and implemented in a Microsoft Excel workbook. This database also contains parameters and factors specific to different categories of equipment (exchangers, evaporators, pumps, boilers, etc.) required for the calculation of investment cost. The calculation of the investment cost uses VBA routines developed to manage the database link and automate the calculation according to the correlations chosen for estimating equipment cost.

The net present value *NPV* is an economic assessment criterion based on the estimate of net cash flows from the process over its lifetime. The discounted cash flows (from year 0 to n) can be written as follows (Chauvel et al., 2001):

$$NPV = -I_0 - WC + \sum_{p=1}^{n} \frac{(V_p - D_p - A_p) \times (1 - a) + A_p}{(1+i)^p} + \frac{WC + I_r}{(1+i)^n} \quad (1)$$

where

- I_0: investment cost;
- WC: working capital necessary for operation of the plant;
- D_p: operating cost for year p;
- V_p: sales income for year p;
- A_p: depreciation for year p;

Table 2 – Fixed parameters for net present value, NPV calculation (from Azzaro-Pantel (2014)).

Parameter	Symbol	Value
Residual investment	I_r	0
Working capital	WC	$15\% \times I_0$
Tax rate	a	33%
Interest rate	i	12%
Depreciation period	n	20 yr
Depreciation method	–	Straight-line

- i: interest rate;
- a: taxation rate;
- I_r: residual investment at year p;

The calculation includes a straight-line depreciation method with a 20-year recovery period. Table 2 gives the fixed parameters used to compute *NPV*. C_{Labor} (€/yr) integrates the correlation proposed in Maroulis and Saravacos (2007):

$$C_{Labor} = t_y \times C_h \times NW \times f_{MP} \quad (2)$$

where

- t_y is annual operating time (h);
- C_h is the labor rate in France, i.e. 33 € h^{-1} (according to INSEE 2008 for the manufacturing industry);
- NW is the required number of workers;
- f_{MO} is a labor cost correction factor (2,5) according to Maroulis and Saravacos (2007).

The annual operating cost D_p includes variable cost, labor cost, and fixed charges.

The calculation of variable costs and revenues requires the estimate of flow rates as well as market prices for raw materials and final product, utilities, and treatments (Appendix A.3). This data was collected from specialized organizations and industries and used for the various products consumed by the milk evaporation process and for products that generate revenue. The price per cubic meter of water used in this work (Appendix A.3) is not a representative average but corresponds to the price of water for an industrial dairy site (confidential source), which includes the costs of water from a natural source plus pumping and treatment costs. In France, the price of water varies significantly between industrial sites. This variation depends on:

- the origin of the water (public water supply system, groundwater or surface water). In the case of the public water supply system, the price of water is negotiated between the client and the municipality's local water authority and varies between €0.50 and €4 per cubic meter. In the case of groundwater or surface water, the company is responsible for the investment cost tied to drilling, pumping and treatment facilities, which is usually quickly depreciated.
- the geographical area in which the industrial site is located.

The cost of wastewater treatment was estimated according to Alvarez (2003) by taking into account the price (per cubic meter) of water used, which includes the price of water pumped and the treatment of water discharged minus the price per cubic meter of water used. The price of milk set here (Appendix A.3) corresponds to a standardized milk with 38 g l^{-1} fat and 32 g l^{-1} protein (CNIEL, 2015).

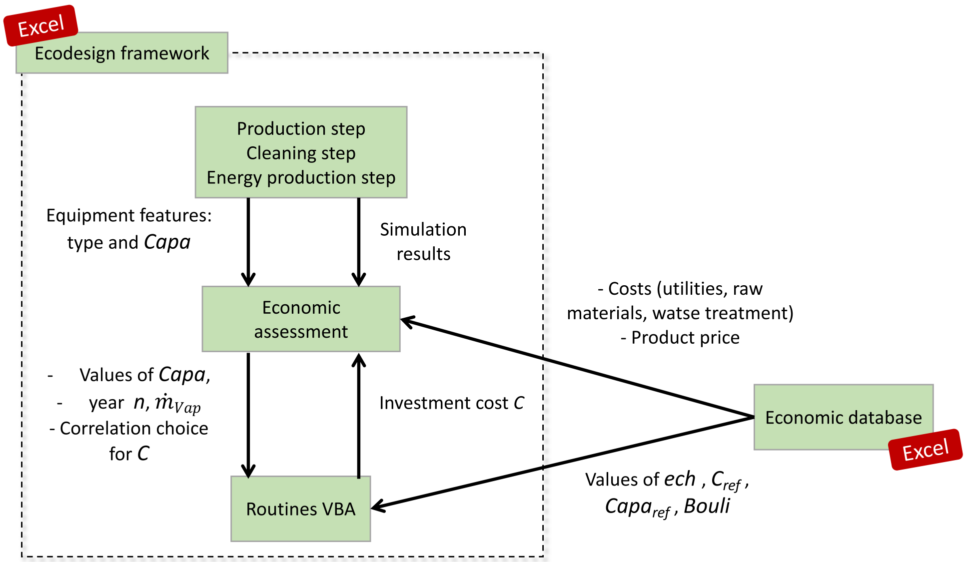

Fig. 7 – Profitability components of the ecodesign framework: C_{ref} is the cost of the reference equipment; *Capa* is the capacity variable considered; $Capa_{ref}$ is the typical variable of the reference equipment; $\dot{m}_{Vap}$ is steam flowrate; *ech* is a scaling factor that is typical of the equipment considered.

For the estimate of capital cost I_0, Guthrie's correlation (Guthrie, 1969), well-known as an extrapolation factor method, makes it possible to estimate the cost of a piece of equipment by similarity to the cost of a piece of reference equipment:

$$C = C_{ref} \times \left(\frac{Capa}{Capa_{ref}}\right)^{ech} \quad (3)$$

In this expression, C is the cost of equipment to evaluate and C_{ref} is the cost of the reference equipment *Capa* is the capacity variable considered (flowrate, power, etc.) or a specific equipment variable (exchange area, volume, etc.); $Capa_{ref}$ is the typical variable of the reference equipment. The exponent *ech* is a scaling factor typical of the equipment considered (pump, heat exchanger, reactor, etc.) (Green and Perry, 2008; Guthrie, 1969; Maroulis and Saravacos, 2007; Turton et al., 2008). Values for the scaling factor are available in the literature. In this study, the datasets used come from Maroulis and Saravacos (2007) as the results of investment cost estimates on evaporators and drying towers are very close to the data provided by a French equipment manufacturer TGE S.A.S. (Thermique-Génie Chimique-Evaporation, Evreux, France) (Appendix A.3).

For the estimation of the investment cost in energy production plants, polynomial correlations developed from the data from McGowan et al. (2009) are used:

(4) Steam generating system using natural gas or fuel oil for a steam flowrate $\dot{m}_{Vap}$ (cost in k$):

$$C = 346.2 + 17.0 \times \dot{m}_{Vap} \quad (4)$$

(5) Steam generation systems using wood chips or wood processing wastes for a steam output $\dot{m}_{Vap}$ (cost in k$):

$$C = 1579.7 + 29.5 \times \dot{m}_{Vap} + 1.8 \times \dot{m}_{Vap}^2 - 9 \times 10^{-3} \times \dot{m}_{Vap}^3 \quad (5)$$

The extrapolation factor values for the Guthrie correlation (Maroulis and Saravacos, 2007) with capacity and cost values for the reference equipment, as well as the polynomials calculated from the data in (McGowan et al., 2009), are all implemented in the economic database purpose-developed in Excel®. The Chemical Engineering Plant Cost Index (CEPCI) was used to adjust process plant construction costs across periods (Seider et al., 2004; Turton et al., 2008). We thus obtain an estimate of the future-year cost of equipment *n* at an initial baseline cost *IC*(*base*) as follows:

$$C(n) = C(base) \times \left(\frac{IC(n)}{IC(base)}\right) \quad (6)$$

IC is the cost index for year *n*, and *IC*(*base*) is the index for the reference-year baseline.

The CEPCI is calculated as follows:

$$CEPCI(n) = 480 + 10 \times (n - 2005) \quad (7)$$

The investment cost is thus calculated in dollars then adjusted with the CEPCI cost index and converted into euros. The conversion rate used in this work is $1 US = €0.7533 (2014).

2.2.5. *Multiobjective optimization*

Multiobjective optimization has permeated all engineering areas and has developed at a rapidly increasing speed, particularly during the last decade for chemical engineering and process design (Hernandez-Rodriguez et al., 2014). There is general consensus that multiobjective optimization methods can be broadly decomposed into two categories: scalarization approaches and evolutionary methods. In scalarization methods, the multiobjective problem is transformed into a single objective one and is well-adapted to well mathematically defined problems with explicit formulations of objectives and constraints, while evolutionary methods are mainly used in black box problems, where objectives and/or constraints are returned by a computer code for each value of the optimization variables. The evolutionary approaches use mainly the concept of dominance to distinguish between dominated and non-dominated solutions. Among these algorithms, NSGA II developed by Srinivas and Deb (1994) is recognized as one of the most efficient multiobjective evolutionary algorithm and was selected in this work.

The ecodesign framework integrates Multigen, a library of genetic algorithms for solving multiobjective problems with variables of different types (continuous, integer, binary), including structural optimization problems (arrangement of unit operations for example). This tool, used in (Morales-Mendoza, 2013; Ouattara, 2011), includes various algorithms derived from the non-dominated sorting genetic algorithm II (NSGA II) and implemented by Gomez (2008). The advantage of NSGA-II over other evolutionary multiobjective optimization techniques is that it determines individual fitness values based on the Pareto dominance relationship and density information between individuals (Gomez et al., 2010).

Multigen can be deployed directly in an Excel workbook as it is coded in VBA as an extension of Microsoft's spreadsheet program. However, Multigen uses VBA coding to control the various simulation tools and automatically calculate economic and environmental criteria: it calls calculation routines and model-linking routines when calculating new individuals (the design solutions) and optimization criteria. Each criterion is then either minimized or maximized by varying the design variables over defined intervals. The boundaries of these intervals are determined based on system knowledge, preliminary optimization studies, or acceptable limits for these decision variables (e.g. limit the exchange surface or minimum operating pressure). Three types of constraints on any variables or criterion can also be applied to the decision variables, i.e. inequality ($r \geq 0$), strict inequality ($r > 0$), equality ($r = 0$).

2.2.6. *Multicriteria decision-making (MCDM)*

The process configuration selected for this framework is performed through a multicriteria decisionmaking (MCDM) process. The objective of MCDM is to help decisionmakers identify a preferred course of action for a given problem. A large variety of approaches have been proposed in the literature (Figueira et al., 2005), but the method commonly used for engineering problems is TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) as it reduces number of parameters involved in its implementation and thus limits subjectivity. We used a modified TOPSIS (M-TOPSIS) assessment (Ren et al., 2007) that chooses the alternative with both the closest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The MCDM method has the benefit of solving the rank reversal and evaluation failure problem observed in the original TOPSIS technique. The calculation steps of the M-TOPSIS method are implemented in Excel® (Morales-Mendoza, 2013; Ouattara, 2011) as follows:

1. Construction of the dimensional performance matrix $n\times$ formed of the n solutions, each formed of values for the m criteria.
2. Normalization of the matrix terms to get comparable non-dimensional values.
3. Multiplication of the matrix by a vector of the coefficients of importance of the criteria: a weighting value can be assigned to each criterion, as expressed by the decision-maker. The standard criteria are noted a_{ij}, where the index i denotes the solution and j denotes the index of the criterion.
4. Calculation of the ideal solution and the worst-case solution: the ideal solution is the set of best values a_j^+ of the matrix for each criterion (maximum value for a criterion to be maximized, and minimum value for a criterion to be minimized), and the worst-case solution is the set of values in the matrix that degrade the criteria the most, denoted as a_j^-.
5. The distance from each solution to the ideal solution D_i^+ and to the worst solution one D_i^- is calculated by an n-dimensional Euclidean distance:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(a_j^+ - a_{ij}\right)^2} \quad (8)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(a_j^- - a_{ij}\right)^2} \quad (9)$$

6. A classification criterion (CC_i) is calculated for each solution, defined as the Euclidean sum:

$$CC_i = \sqrt{\left(D_i^+ - \min\left(D_i^+\right)\right)^2 + \left(D_i^- - \min\left(D_i^-\right)\right)^2} \quad (10)$$

7. Solutions are ranked according to (CC_i); the closer (CC_i) is to zero, the better the solution.

2.2.7. *Interconnection between the different tools*

Fig. 8 presents the data exchange between component tools that make up the methodological framework implemented in this study. The methodology follows the guidelines that were originally developed for chemical processes (for more details on the implementation (Morales-Mendoza et al., 2018).

Multicriteria analysis tools (in particular, the VBA routines) are included in the main interface, which drives all the other tools. The criteria from the environmental and economic analyses serve as optimization criteria for Multigen, which modifies the design variables as it searches for optimal solutions. The new values of these variables then serve as new parameters for the different production, cleaning or energy production models.

This methodological framework is designed to position multiobjective optimization to support ecodesign. This has been illustrated in previous work (Madoumier et al., 2020) that developed an ecodesign approach for a dairy evaporation process combining a cleaning kinetics model with fouling kinetics hypotheses. It was shown that integrating both cleaning and production in the evaporator process optimization can bring improvements over both industrial practice and the optimization of cleaning parameters considered separately, it was demonstrated that predicting fouling kinetics, even with arbitrary fouling kinetics laws, can help estimate the potential economic savings and reduced environmental impact. However, comparative analyses between solutions without the use of the optimization tool can also be implemented when optimization is not required, as emphasized in the application section.

3. Results: applications of the framework to milk evaporation

This comprehensive set of inventory calculation, environmental assessment, economic analysis and optimization tools provides the core building blocks of the methodological framework for the ecodesign of a process. The process design can thus be studied, and the best compromise between technical, economic and environmental criteria can be determined. This section illustrates the potential of the approach through

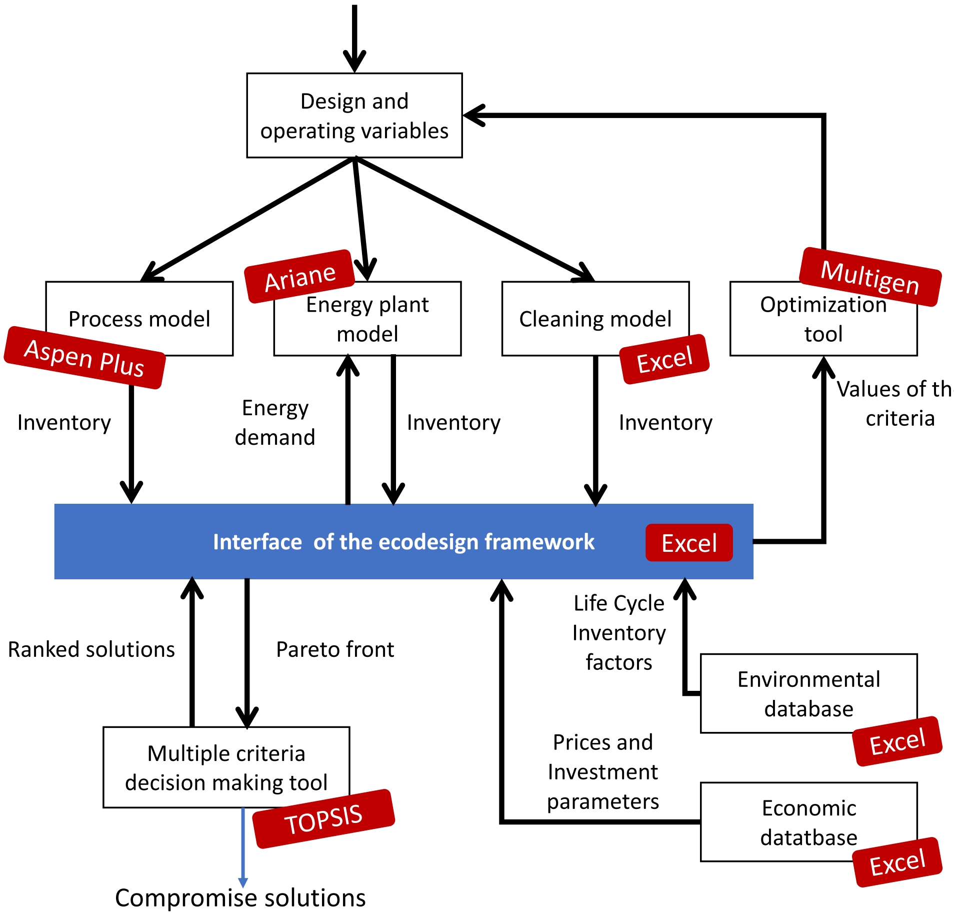

Fig. 8 – Data flow between tools within the ecodesign framework.

Table 3 – Data for the study on the influence of the number of effects of an evaporation process.

Process data	
Evaporation process	Inspired from an industrial evaporator, without vapor compression for preheating and without thermocompression to simplify comparison and design
Flowrate of treated milk	$20\,t\,h^{-1}$
Cleaning sequence	Reference sequence
Energy production	Natural-gas-fired 6.7-bar steam power station
Functional unit	1 kg milk (evaporator input)
Design variables	
Number of effects	3, 4 or 5
Calculated variables	
Process	Evaporator capital cost and vapor consumption
Energy production	Fuel consumption
Assessment criteria	
Economic	net present value, discounted payback period, internal rate of return
Environmental	Climate Change and Singlescore

two ecodesign case studies on the milk evaporation process as a preconcentration step for milk powder production are proposed (Fig. 2).

1. Case study #1 “Evaporator design” illustrates the potential of the methodological framework to determine the number of effects of evaporators in the production phase. It shows the value of coupling modeling and simulation to design the evaporator according to economic and environmental criteria. No multiobjective optimization was necessary for this first study. We study a classic of evaporator design by varying, the number of effects (from three to five) for the same production objective. The cleaning phase is included in the multicriteria analysis, with parameters fixed according to the reference cleaning-in-place sequence.
2. Case study #2 “Choice of primary energy source” uses the methodological guidelines of the overall proposed framework for a strategic design choice in which the proposed solutions are evaluated according to sustainable development criteria: the multiobjective optimization and multicriteria decision making tools are used to search for the best compromise between environmental impact and profitability among various fuels, and to select an appropriate primary energy source accordingly.

3.1. *Design of a milk evaporator by coupling modelling and simulation (case study #1)*

The methodological framework is used here to design an evaporator treating milk. Various arrangements of the items

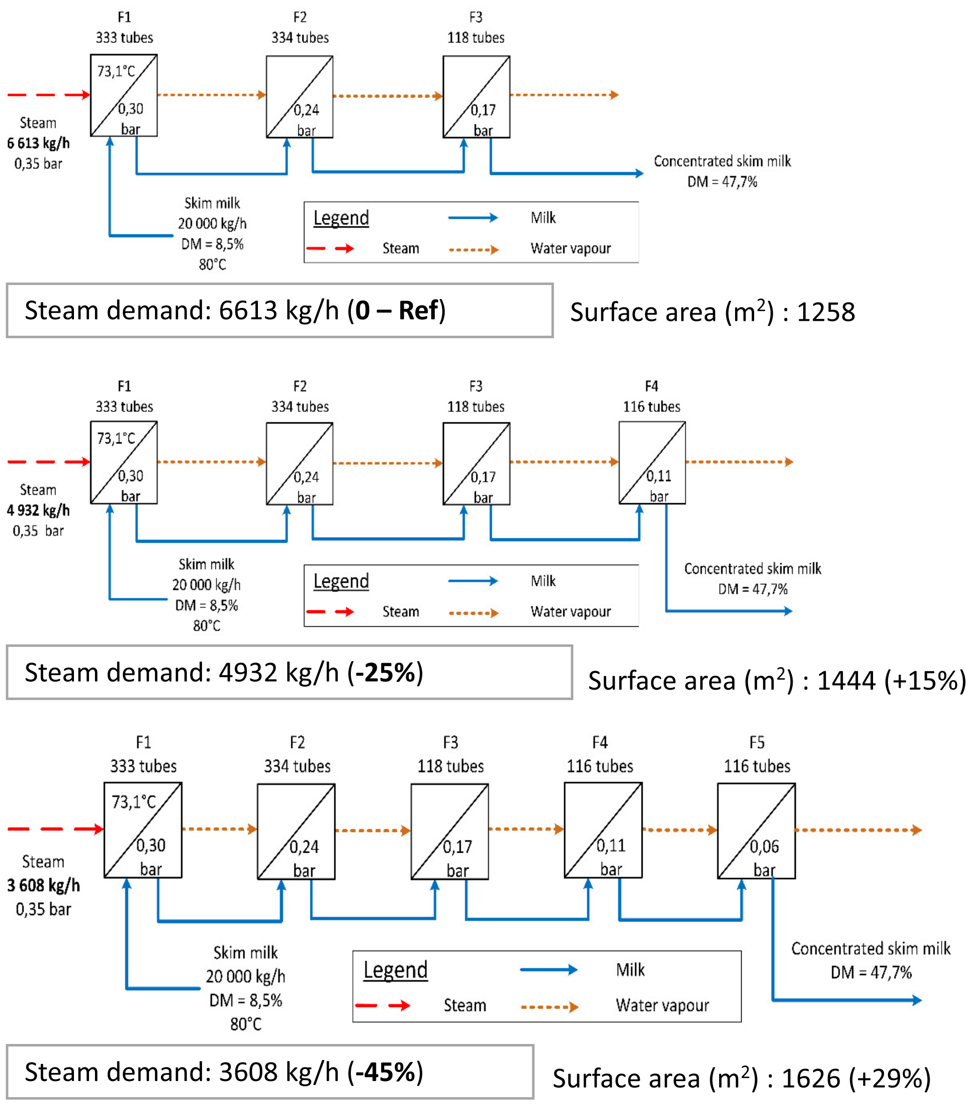

Fig. 9 – Process flowsheet for the evaporation of skim milk (20 t h^{-1}) featuring different effects.

Table 4 – Typical features of the three design solutions.

	Effect number		
	3	4	5
Total surface area (m^2)	1258	1444	1626
Vapor consumption (kg h^{-1})	6613	4932	3608

composing the evaporator (tubular evaporator bodies, separators, preheaters, compressors) and their associated flows are modeled in order to assess their economic and environmental performances. A simplified-design evaporator was sized in three configurations depending on number of effects (3, 4 or 5). The evaporator design is viewed as simplified, since neither milk preheating nor vapor recompression has been considered (it must be yet highlighted that recent evaporators have mainly be installed with mechanical vapor recompression): the water vapor of one effect is simply used to heat the next effects in the sequence. Table 3 presents the data of the process studied.

As expected, the higher the number of effects, the lower the calculated steam demand (Fig. 9): the steam demand calculated by the simulator is 4932 kg/h for four effects (−25% compared with the reference) and 3608 kg/h for five effects (−5% compared with the reference) (see Fig. 9 and Table 4).

The optimal number of effects thus depends on the balance between costs (investment costs, which directly depend on the number of effects, and energy costs, as identified above) and environmental impacts. In addition to these conventional inventories of costs for evaporator design, the methodological framework provides economic and environmental data in the form of indicators that are used as criteria for the analysis. The use of the methodological approach makes it possible to quantify these criteria and then assess the compromise between cost and environmental impact. Note that energy consumption creates a variable cost, but the energy source (natural gas here) also has an environmental impact induced by its extraction, distribution and production.

From an economic perspective, the five-effect evaporator is more attractive regardless of economic indicator studied (Table 5), as it achieves a higher long-term benefit than with three and four effects, with a shorter payback period and a higher internal rate of return. Using the methodological framework, the find that despite the higher investment cost of the five-effect evaporator, the fuel savings achieved make the process more profitable; the lower investment cost in the three-effect evaporator does not lead to a faster return on investment. From an environmental perspective, the five-effect evaporator logically has the lowest impact, since the environmental impact of the equipment design is considered

Table 5 – Data and criteria for economic and environmental analysis. Percentages indicate the relative deviation from 4 effects. DALY: disability-adjusted life years.

	3 effects	4 effects	5 effects
Net present value (after 20 years (M€)	1.05 (−72%)	3.72	5.78 (+55%)
Payback period (yr)	10.81 (+84%)	5.88	4.72 (−20%)
Internal rate of return	17% (−38%)	28%	35% (+26%)
Investment cost (M€)	3.03 (−7%)	3.26	3.49 (+7%)
Variable cost (M€/yr)	55.36 (+1%)	54.72	54.21 (−1%)
Fuel consumption (t/yr)	2975 (+33%)	2231	1646 (−26%)
Singlescore with ReCiPe	1.08×10^{-1} (+27%)	$8.50.10^{-2}$	6.67×10^{-2} (−22%)
Singlescore with Impact 2002+	2.44×10^{-4} (+30%)	1.87×10^{-4}	1.43×10^{-4} (−24%)
Climate change health with ReCiPe (DALY kg input milk^{-1})	1.42×10^{-6} (+30%)	1.10×10^{-6}	8.40×10^{-6} (−23%)
Climate change ecosystems with ReCiPe (species yr kg input milk^{-1})	8.05×10^{-9} (+30%)	6.21×10^{-9}	4.76×10^{-9} (−23%)
Global warming with Impact 2002+ (kg CO_2^{eq} kg input milk^{-1})	0.97 (+31%)	0.74	0.56 (−24%)

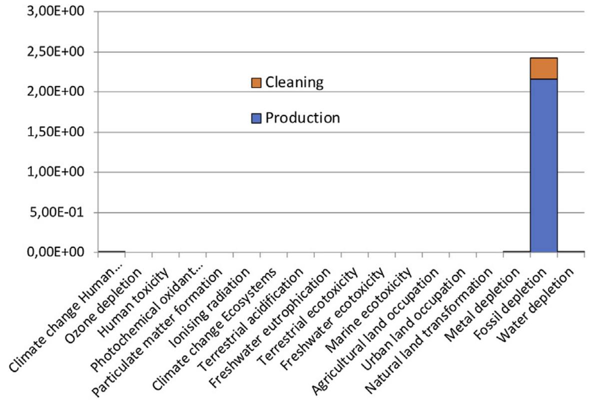

Fig. 10 – Scores, in kg of equivalent polluting substance per kg treated milk, for midpoint categories with ReCiPe: 4-effect evaporator.

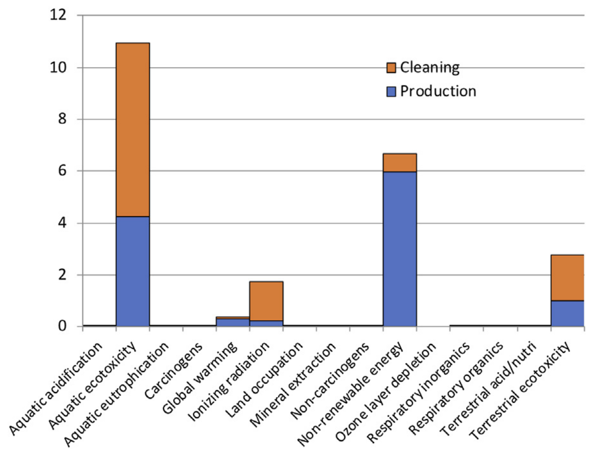

Fig. 11 – Scores, in kg of equivalent polluting substance per kg of treated milk, for midpoint categories with Impact2002+: 4-effect evaporator.

negligible, and its fuel consumption is less than that of the three- and four-effect evaporators. An ecodesign study may require further analysis of contributions to environmental impact.

Depending on the LCA method used, the methodological framework can evaluate the midpoint categories and damages to identify major contributions to environmental impact.

Figs. 10 and 11 chart the various contributions to environmental impact for the ReCiPe and Impact2002+ methods, respectively, in the case of the four-effect evaporator. With ReCiPe (Fig. 10), consumption of fossil resources is the dominant impact compared to the other midpoint categories, whereas for Impact 2002+ (Fig. 11), the key impact is on aquatic environments.

Regardless of the methodology, the production phase has a higher environmental impact than the cleaning phase for the indicators related to use of fossil resources and global warming. Based on the single impact score according to ReCiPe and Impact 2002+ (Fig. 12), the cleaning phase has increasing impacts with increasing number of effects, with a decrease in energy consumption in the production phase. The relative values are what we are considering here.

This illustrates the value of the methodological framework for determining the ecodesign levers of the process: once the process has been optimized, opposite trends could yet be observed with a predominant contribution of the cleaning phase compared to the production phase, which identifies cleaning as a new target for overall process optimization. However, this observation only holds valid for the purposes of this work, as we did not consider the whole design of clean-in-place (CIP) and production (evaluation of the CIP inventories requires modeling of cleaning solutions and mire in-depth knowledge of the sequences used with the studied evaporator (which was investigated in Madoumier et al. (2020).

The proposed framework thus provides an accurate environmental impact assessment and profitability analysis of the evaporation process to guide design-option decisions: the different criteria are calculated directly from the inventories of the proposed design solutions, which leads to a direct evaluation of compromise solutions from an ecodesign perspective. As the calculation of inventories also takes into account the cleaning phase, the contribution of production and cleaning can be positioned in order to identify the hotspot of the global process and suggest improvement options. The assessment of economic and environmental criteria could be further improved by taking into account the whole milk powder production chain (delivery, drying, packaging) for a better assessment of profitability, and by using design tools that are better adapted to evaporation processes, including vapor recycling and recompression and preheating, which would require further evaluation of the various process configurations.

3.2. *Choice of primary energy source by multicriteria assessment (case study #2)*

In the second case study, the methodological framework is used to guide the selection of a fuel that would provide energy for the reference evaporation plant. The target is to find the best compromise between cost and environmental impact from among natural gas and heavy fuel oil, which are the most widely consumed fuels in the agri-food indus-

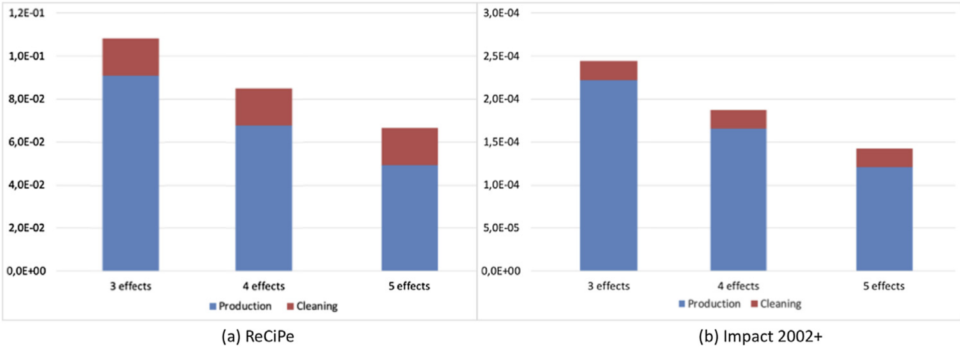

Fig. 12 – Contribution to the single impact score (aggregated value) of cleaning and production phases according to the ReCiPe (a) and Impact 2002+ (b) methods.

Table 6 – Data for fuel selection.

Process data	
Evaporation process	Industrial evaporator with condenser, pasteurizer and preheaters
Processed milk flow	$20\,t\,h^{-1}$
Cleaning sequence	Reference sequence
Energy production	Vapor production at 6.7 bar
Design variables	
Primary energy source	Natural gas, heavy fuel, wood chips
Observational variables	
Energy production cost	• Boiler capital cost • Fuel unitary cost (€/kg or €/LHV) and yearly consumption
Environmental impact of energy	• Production impact/fuel extraction • Emission factor (CO_2, NO_X, SO_2, etc.) as a function of fuel
Assessment criteria	
Economic	Net present value, payback time, internal rate of return
Environmental	Climate change, fossil fuel consumption

try (French Ministry of Agriculture, Food and Forestry, 2009; French Ministry of Agriculture, Food and Forestry, 2012), and wood chips, which are a major wood-industry co-product (Deglise and Donnot, 2004). For wood chips, two scenarios were studied: with and without carbon neutrality. The carbon neutrality scenario assumes a carbon-neutral balance, i.e. CO_2 emissions due to wood combustion are considered zero. Life cycle studies often consider that CO_2 emissions from biomass are offset by the amount of CO_2 fixed during biomass growth (McKechnie et al., 2010). However, recent studies seem to show that this carbon neutrality hypothesis is incorrect, particularly due to the time interval between wood harvest and complete regrowth (Holtsmark, 2015). The framework is used to calculate the process inventories (that will be fixed) and the inventory of energy production plant with the selected fuel. Key case-study data is given in Table 6. The inventories serve to evaluate the environmental impact and profitability of the evaporation process associated with each fuel. For each fuel, the costs vary according to several factors:

- capital cost of the boiler, which varies because hourly fuel consumption depends on the lower heating value (LHV) of the fuel: boiler size varies with the fuel for the same energy production output;
- cost of the fuel (per kilogram or per kWh LHV);
- annual cost of fuel consumed, which depends of the LHV of the fuel.

The combined set of economic and environmental criteria are used to rank the four alternatives via the M-TOPSIS method (Table 8) with the same weighting for each criterion. Four different combinations of criteria are tested in order to study the influence of the choice of analysis criteria on the best trade-off determined.

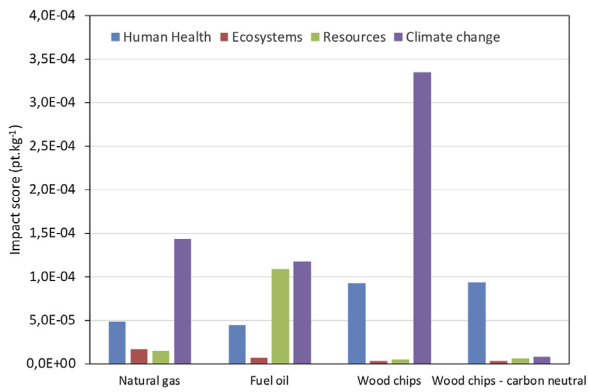

Fig. 13 – Damage scores in endpoint categories for different fuels according to Impact 2002+.

From an economic perspective, the use of wood chips is more profitable long-term (Table 7): the profit obtained after 20 years of operation is higher, as its higher consumption compared to other fuels is compensated by a sufficiently competitive price per unit. However, the higher cost of investment in the wood boiler slightly lengthens the payback time needed to compensate for this consumption, and thus reduces the internal rate of return. However, the values of payback times have a comparable order of magnitude.

From an environmental perspective, the damage scores (Figs. 13 and 14) show that the use of wood chips has a very detrimental effect on the environment and humans (compared to other fuels) if the CO_2 emissions of the chips are not considered neutral: the difference is particularly significant in the ‘Climate change’ damage category using the Impact 2002+ method. This case study shows the importance of the ground assumptions for environmental analysis, especially when biomass is involved in the impact calculation.

Table 7 – Economic and environmental criteria values for each fuel alternative (PDF: potentially disappeared fraction of species).

	Scenarios			
	Natural gas (reference)	Fuel	Wood chips	Wood chips – carbon neutral
Profitability				
Net present value (M€)	8.26	9.34 (+13%)	9.54 (+16%)	9.54 (+16%)
Internal rate of return (%)	47	51 (+9%)	42 (−10%)	42 (−10%)
Discounted payback time (yr)	3.64	3.38 (−7%)	3.95 (+9%)	3.95 (+9%)
Environmental impact – Impact 2002+				
Human health (DALY kg input milk^{-1})	1.05×10^{-5}	2.14×10^{-5} (+104%)	4.81×10^{-5} (+357%)	4.81×10^{-5} (+357%)
Ecosystems (PDF m^2 yr kg input milk^{-1})	4.94×10^{-6}	7.52×10^{-6} (+52%)	1.65×10^{-5} (+235%)	1.65×10^{-5} (+235%)
Resources (MJ kg input milk^{-1})	4.40×10^{-5}	4.48×10^{-5} (+2%)	1.51×10^{-5} (−66%)	1.51×10^{-5} (−66%)
Climate change	3.89×10^{-5}	5.10×10^{-5} (+31%)	1.44×10^{-4} (+270%)	1.43×10^{-5} (−63%)
Singlescore	9.84×10^{-5}	1.25×10^{-4} (+27%)	2.24×10^{-4} (+127%)	9.41×10^{-5} (−4%)
Environmental impact – ReCiPe				
Human health (DALY kg input milk^{-1})	1.32×10^{-2}	1.87×10^{-2} (+41%)	4.39×10^{-2} (+233%)	8.31×10^{-3} (−37%)
Ecosystems (species yr kg input milk^{-1})	1.72×10^{-2}	2.30×10^{-2} (+34%)	7.02×10^{-2} (+307%)	4.69×10^{-2} (+172%)
Resources ($ kg input milk^{-1})	1.81×10^{-2}	1.89×10^{-2} (+4%)	5.01×10^{-3} (−72%)	5.01×10^{-3} (−72%)
Single score	4.86×10^{-2}	6.06×10^{-2} (+25%)	1.19×10^{-1} (+145%)	6.02×10^{-2} (+24%)

Table 8 – TOPSIS classifications according to different combinations of criteria.

	Fuel			
	Natural gas	Heavy fuel	Wood chips	Wood chips-carbon neutral
Three economic criteria, climate change, resources (Impact 2002+)	2	3	4	1
Three economic criteria, single score (ReCiPe)	1	2	4	3
Net present value, single score (Impact 2002+)	2	3	4	1
Net present value, single score (ReCiPe)	1	3	4	2

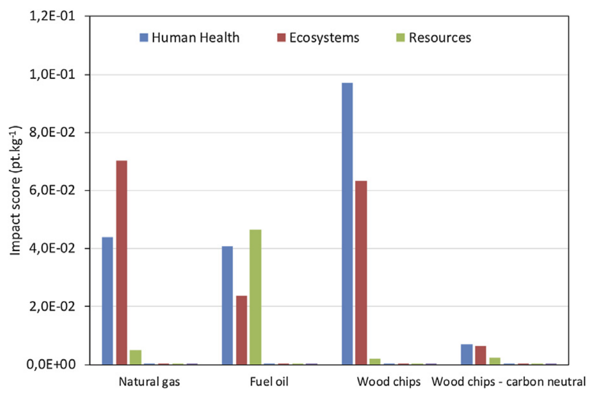

Fig. 14 – Damage scores in endpoint categories for different fuels according to ReCiPe.

Regardless of the LCI criteria and impact assessment methods used, the single composite score (Table 7) is higher for carbon-neutral wood chips compared to natural gas according to the Impact 2002+ system but lower according to the ReCiPe system. Moreover, the difference between the scores is significant (12% in the case of Impact 2002+ and 200% in the case of ReCiPe), which highlights the influence of assessment method on the calculated environmental impact and consequently on the decision-making process. The ranking of the four alternatives is therefore strongly influenced by the environmental indicators.

Regardless of LCA analysis methodology, M-TOPSIS always ranks non-carbon neutral chips as the worst trade-off. Indeed, by assigning the same decisional weight to environmental and economic criteria, the environmental impact of wood chips, which is particularly high when CO2 neutrality is not factored in, penalizes this alternative compared to other solutions which emerge closer to the 'ideal' solution determined by M-TOPSIS. M-TOPSIS always ranks natural gas in first position when the environmental impact is determined by the ReCiPe methodology, whereas the Impact 2002+ method gives carbon-neutral wood chips as the best compromise. This variation is due to the abovementioned differences in the calculation of environmental impact. Taking only net present value as an economic criterion does not influence the ranking under the Impact 2002+ method. With the ReCiPe methodology, M-TOPSIS ranks heavy fuel oil in third place, since the net present value is better for wood chips.

M-TOPSIS with these four combinations of criteria directly provides a ranking of solutions that co-considers all criteria simultaneously. It also highlights the value of varying the objectives of the strategic decision, which is reflected in the choice of decision criteria (net present value with or without internal rate of return, environmental impact criteria). The methodological framework was used to analyze alterna-

Table 9 – Modeling a new fuel (i.e. wood chips) in the Ariane simulator. The characteristics of natural gas and heavy fuel oil provided in the Ariane database are also given for comparative purposes.

Parameter	Wood chips	Natural gas	Heavy fuel oil (fuel oil)
Bulk purity (% weight)	39.20	99.90	99.69
Sulphur (% weight)	0.01	0.00	0.31
LHV 0 °C (th t^{-1})	3170.00	–	9450.00
LHV 0 °C (kWh N m^{-3})	–	11.30	–
Molar weight (g mol^{-1})	24.0	16.0	120.0
C/H ratio (–)	8.33	3.00	8.00
Storage temperature (°C)	15.0	15.0	15.0
Storage pressure (bar)	1.0	10.0	1.0
Thermal capacity (J g^{-1} K^{-1})	2.114	2.261	2.905

Table 10 – Average dry wood composition according to Rabot-Querci (2006) and forest chip composition calculated from this average composition and the sulphur content of the chips given in Rector et al. (2013). The 30% value for wood chip moisture content is taken from Deglise and Donnot (2004).

Compound	Dry wood (% weight)	Wood chips (% weight)
C	50.00	35.00
H	6.00	4.20
O	44.00	30.80
S	0.01	0.01
H_2O	0.00	30.00

tives for the strategic choice of the primary energy source for the evaporation process from an ecodesign perspective. The tools used made it possible to predict the inventories related to fuel-dependent power generation, and to calculate criteria for economic and environmental analysis. M-TOPSIS assesses the best trade-off in a rationalized basis. The criteria are thus considered simultaneously, which is an advantage over conventional methods where the design is carried out with the single objective of profitability and the minimization of environmental impact is carried out through a posteriori analysis. A further advantage is the possibility of using different criteria for decision support, which makes it possible to adapt to the potentially different demands of the decision-makers.

4. Conclusion

This work developed a methodology for the ecodesign of an agrifood transformation process in order to promote the implementation of ecodesign principles in food-farming industries. This framework combines systemic analysis, modeling, multiobjective optimization, and multicriteria decisionmaking tools initially developed for processes in the chemical industry sector. The skim milk evaporation process was chosen as the target application of the methodological framework because it is one of the most energy-intensive processes in the dairy sector and it encompasses multiple design solutions with high potential for optimization. In addition, only a few systemic approaches to ecodesign are available in the literature. The Aspen Plus process simulator, which has conventionally been used for modeling and simulation of chemical and petrochemical processes, was adapted here by integrating models of milk properties (heat capacity, boiling delay, thermal conductivity, density, viscosity, surface tension) and product-side exchange coefficient models. The work on selecting the milk properties model highlighted the need for property modeling research, as an extensive literature search could not find a full set of property models suitable for milk in the temperature and concentration ranges used in evaporation processes. The inventory calculation tools developed have been embedded into our core methodological framework, which includes a modeling tool for energy production plant simulation, a cleaning model, economic and environmental assessment methods, a multiobjective optimization algorithm, and a multicriteria decision support method. The economic and environmental analysis methods make it possible to calculate criteria that can then be used to compare different scenarios or optimize the process from an ecodesign perspective. Two ecodesign case-studies were performed:

- Three evaporator design solutions were modeled and compared. This case study demonstrated the value of economic and environmental analysis tools, as well as the need for design tools adapted to the evaporation process.
- Different fuels for the production of process energy were compared using multiobjective optimization and multicriteria analysis methods. A strategic choice integrating potentially contradictory objectives can thus be made in a rational manner using the tools and methods implemented in the methodological framework.

Finally, the proposed approach provided guidelines for ecodesigning the milk evaporation process and agrifood processes in general, through a strategy combining experimental work with modeling, simulation, optimization and decision-making. This methodological framework can thus be used for strategic decision-making and for reducing the environmental footprint of agrifood processes.

This work points to a number of perspectives. Extension of the ecodesign approach to agrifood processes requires further effort to gain new knowledge, in particular in the modeling of product properties, i.e. coefficient exchanges in the case of

Table 11 – Combustion and efficiency data stratified by fuel.

Fuel	Boiler features		Emission factors		
	Yield (Felder and Dones, 2007)	Air excess (Weston, 1992)	NO_X	CO/CO_2 Ratio	Dust
Natural gas	0.96	10%	2745 mg N m^{-3}	0.039%	36.6 mg N m^{-3}
Heavy fuel	0.94	10%	7117 g t^{-1}	0.035%	988.5 g t^{-1}
Wood chips	0.85	25%	2653 g t^{-1}	0.272%	1326.4 g t^{-1}

evaporation and cleaning, and further development of modeling and design tools adapted to agrifood processes. A further step would be to develop the same approach combining evaporation and drying.

In the short term, integrating the entire milk powder production plant would make it possible to complete ecodesign studies that factor in economic and environmental standards consistent with real-world industry practice and to equip the framework for application to other processes (such as standardization operations, membrane operations, and drying) and their associated models. This modeling work would be valuably supported by a modeling-simulation tool adapted to agrifood processes, including models of physical–chemical properties and unit operations, which would enable easy integration of models from the literature or other works.

In the medium term, one or more tools for process energy integration, such as pinch analysis, could enrich the ecodesign approach by enabling a more thorough systemic study of different evaporator design solutions, and therefore of production plants that usually have a high utility power demand. Coupled with the process simulator adapted to agrifood processes and optimization techniques to search for the optimal superstructure of the process (such as combinatorial optimization or graph theory), these tools would enable efficient guided searches for possible solutions for process ecodesign.

In the long term, we anticipate that the acquisition of new knowledge and its integration into the methodological framework will make it possible to increase the relevancy and accuracy of ecodesign studies.

- Enrichment of the LCI databases, or the acquisition of relevant data for LCA, would make it possible to calculate more relevant environmental indicators, such as the regionalized impact of biomass as a primary energy source, or the impact of milk production route, such as organic vs conventional.
- The problem of wastewater treatment in particularly critical issue in the management of the cleaning phase. This problem could be addressed by integrating station design or by modeling wastewater treatment (in cases involving on-site treatment facilities).
- Cleaning optimization according to the process control is also crucial to the production phase. Empirical models would make it possible to estimate the nature and quantity of fouling depending on key process conditions. The proposed strategy could be then used to determine the appropriate clean-in-place protocol for the production phase.
- The integration of quality criteria, such as product denaturation and health risk, would make it possible to search for the best compromise between cost, environmental impact, and quality. Again, this would require a substantial modeling effort to predict the impact of process control on the physical–chemical transformations undergone by the product. For example, the calculation of residence time of milk in heat treatment equipment, coupled with knowledge of both protein denaturation kinetics and protein content in the product, would make it possible to predict the fraction of denatured proteins.

The integration of quality criteria is pivotal to wider acceptability and adoption of ecodesign principles in agrifood industries. Generalizing ecodesign in the agrifood sector will require a lot of experimental work and modeling research to compile key knowledge and validate predictive performances, but it will also provide solutions to address the key challenges facing the sector.

Conflict of interest

None declared.

Appendix A.

A.1 Specification of a new fuel in Ariane

A new fuel representing wood chips has been added to Ariane's database in order to carry out comparative studies with other fuels or to model a wood-fired production plant for plant process ecodesign. The parameters presented in Table 9 have been used. The composition of the wood is the starting point for estimating the parameters of this fuel. As wood composition varies with species (oak, beech, fir, etc.), we took an average composition (Table 10 based on Rabot-Querci (2006). Considering a moisture content of 30% (Deglise and Donnot, 2004) and a sulphur content of 0.01% (Rector et al., 2013), which are necessary to specify a fuel parameter in Ariane, we were able to calculate a mean composition for wood chips (Table 10).

Based on this composition, we were able to calculate the mass purity and C/H ratio (mass of carbon to mass of hydrogen) of the chips. The mass purity gives the ratio of carbon and hydrogen atoms compared to the other fuel compounds (P. Baudet, Prosim S.A., personal communication). By omitting sulphur, the composition of dry wood gives the raw formula $CH_{1.44}O_{0.66}$ for the wood molecule (Rabot-Querci, 2006)). Molar mass of the fuel is therefore set at 24.0 g mol^{-1}.

The lower heating value [kJ kg^{-1}] (LHV)and heat capacity of the chips were calculated from the formulas used in Deglise and Donnot (2004). The higher heating value [kJ kg^{-1}](HHV) of a wood is used to calculate its dry LHV, which can then be used to calculate the wet LHV:

$$HHV = 47,500 \times X_C - 2380 \quad (11)$$

where X_C is the carbon mass fraction;

$$LHV_{anhydrous} = HHV - \Delta H_{Vap} \times \frac{M_{H_2O}}{2 \times M_H} \times X_H \quad (12)$$

where ΔH_{Vap} is latent heat of vaporization of water, X_H is hydrogen mass fraction, and M_{H_2O} and M_H are the molar masses of water and hydrogen, respectively

$$LHV_{wet} = (1 - X_{H_2O}/100) \times LHV_{anhydrous} - (X_{H_2O}/100) \times \Delta H_{Vap} \quad (13)$$

With typical features of wood (see Table 10) (dry wood), value for latent heat of vaporization of water at 0 °C of 2496.6 kJ kg^{-1}, and 30% moisture content, the wet LHV value is 13,265 kJ kg^{-1}, which is 3170 th/t (therms per ton). The heat capacity is calculated from the anhydrous heat capacity and moisture content:

$$Cp_{anhydrous} = 0.1031 + 0.003867 \times T \quad (14)$$

where T (in K) is the storage temperature at 15 °C (288.15 K);

$$Cp_{wet} = \frac{Cp_{anhydrous} \times 100 + Cp_{H_2O} \times X_{H_2O}^{anhydrous}}{100 + X_{H_2O}^{anhydrous}} \quad (15)$$

	Substance	LCI in SimaPro	Database
Input	Milk	Cow milk, 4% fat-corrected and 3.3% protein-corrected	Added in SimaPro from data in Nguyen et al. (2013)
	NaOH	Caustic soda (concentrated) E	Industry data 2.0
		Caustic soda, 50% in H2O, production mix, at plant/RER S	Ecoinvent
	HNO_3	Nitric acid, 50% in H2O, at plant/RER S	Ecoinvent
	Water	Drinking water, water purification treatment, production mix, at plant, from groundwater RER S	ELCD
		Drinking water, water purification treatment, production mix, at plant, from surface water RER S	ELCD
		Tap water, at user/RER S	Ecoinvent
		Process water, ion exchange, production mix, at plant, from groundwater RER S	ELCD
		Process water, ion exchange, production mix, at plant, from surface water RER S	ELCD
	Fuels	Natural gas, production DZ, at evaporation plant/RER S	Ecoinvent
		Natural gas, high pressure, at consumer/FR S	Ecoinvent
		Wood pellets, $u = 10\%$, at storehouse/RER S	Ecoinvent
		Light fuel oil, at regional storage/RER S	Ecoinvent
		Heavy fuel oil, at regional storage/RER S	Ecoinvent
		Wood chips, mixed, from industry, $u = 40\%$, at plant/RER S	Ecoinvent
	Electricity	Electricity, high voltage, production FR, at grid/FR S	Ecoinvent
		Elect. mix, AC, consumption mix, at consumer, <1 kV FR S	ELCD
		Elect., low voltage, production FR, at grid/FR S	Ecoinvent
		Electricity mix, AC, consumption mix, at consumer, 1–60 kV FR S	ELCD
		Elect., medium voltage, production FR, at grid/FR S	Ecoinvent
Output	Waste water	Treatment, sewage, to wastewater treatment, class 1/CH S	Ecoinvent
		Treatment, sewage, to wastewater treatment, class 2/CH S	Ecoinvent
		Treatment, sewage, to wastewater treatment, class 3/CH S	Ecoinvent
		Treatment, sewage, to wastewater treatment, class 4/CH S	Ecoinvent
		Treatment, sewage, to wastewater treatment, class 5/CH S	Ecoinvent
		Waste water treatment, industrial waste water according to the Directive 91/271/ (organic contaminated EU-27) S	ELCD

where $X_{H_2O}^{anhydrous}$ is the mass percentage of water in relation to the mass of the anhydrous fuel. Considering a water thermal capacity at 15 °C of 4.196 kJ kg^{-1} K^{-1} and a moisture content on dry of 43% (30% humidity, the wet heat capacity of the chips is thus estimated at 2.111 kJ kg^{-1} K^{-1}, i.e. 0.505 cal g^{-1} K^{-1}.

The efficiency of a boiler depends on the fuel used: each fuel will have its own type of boiler that will output a certain efficiency, and also a certain flue gas composition, as the combustion will not be the same (stoichiometry, mixture) depending on the fuel and the associated combustion system. We thus complied some typical average data values for each fuel (Table 11) and are specified in Ariane for the study of each fuel. The emission factors are calculated according to the LHV of the fuel and the emission factors in g GJ^{-1} LHV provided by citeA (Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique) for wood, heavy fuel oil and natural gas (Fontelle et al., 2014).

A.2 Life cycle inventories from SimaPro

This section presents the list of LCIs selected for the inputs and outputs of the system studied in this work. LCIs labeled S (for system) in SimaPro were selected because they contain inventory data for the entire production chain of a material, in contrast to SimaPro LCIs labeled U (for unit) which are associated with processes intended to be linked to other steps in the production chain for a complete life cycle analysis in SimaPro.

	Product	Unit price	Source
Expenses	Production milk, France, 2014	0.365 € l^{-1}	CNIEL (2015)
	Soda, 30% in solution	0.200 € kg^{-1}	M. Dif (Elodys International, personal communication)
	Nitirc acid, 56% in solution	0.200 € kg^{-1}	M. Dif (Elodys International, personal communication
	Natural gas, industry customers, GDF-Suez prices for a consumption range between 30 and 350 MWh LHV, 2014	0.054 € $(kWh\ LHV)^{-1}$	Service de l'observation et des statistiques (2015)
	Natural gas, industry customers, GDF-Suez prices for a consumption range between 350 and 5000 MWh LHV, 2014	0.049 € $(kWh\ LHV)^{-1}$	Service de l'observation et des statistiques (2015)
	Natural gas, industry customers, GDF-Suez prices for a consumption greater than 5000 MWh LHV, 2014	0.037 € $(kWh\ LHV)^{-1}$	Service de l'observation et des statistiques (2015)
	Very low sulphur heavy fuel oil, 2014	0.517 € kg^{-1}	Service de l'observation et des statistiques (2015)
	Wood chips, delivered, France, 2014	0.025 € kWh^{-1}	CODA Stratégies (2014)
	Electricity supplied to industry according to the Eurostat survey (European Commission), consumption between 20 and 150 GWh, 2014	0.143–0.060 € kWh^{-1}	Service de l'observation et des statistiques (2015)
	Surface (river) water pumped and treated	0.850 € m^{-3}	Confidential source
	Waste water treatment	0.750 € m^{-3}	Alvarez (2003); Lactalis S.A., Pontivy, France
Incomes	Skimmed milk powder spray for human consumption, 2014	2.636 € kg^{-1} HT départ usine	CNIEL (2015)
	Cream of milk, for external clients, 2014	3.830 € kg^{-1}	Beuralia S.A.S., Paris, France

A.3 Market prices for expenses and incomes computation

This section presents the unit prices of products entering and exiting the milk evaporation process in the production or cleaning phase.

A.4 Parameters for Guthrie correlation: Maroulis and Saravacos (2007)

This section presents the base costs and the extrapolation factors for estimating capital investment cost of equipment

Equipment type	Reference year	Capacity or dimension	Base cost, C_{base}	Extrapolation factor, *ech*
Tubular evaporator	2007	m^2 (exchange area)	20	0.7
Forced Flow Evaporator	2007	m^2 (exchange area)	100	0.7
Thin-film heat exchanger	2007	m^2 (exchange area)	5	0.95
Tubular exchanger	2007	m^2 (exchange area)	3	0.65
Plate heat exchanger	2007	m^2 (exchange area)	7	0.6

using the Guthrie correlation (Guthrie, 1969). The data is from Guthrie (1969); costs are in k$, and the capacity or size of the reference equipment is always equal to the unit.

Declaration of Competing Interest

The authors report no declarations of interest.

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