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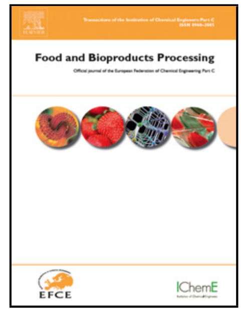

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Including cleaning and production phases in the eco-design of a milk evaporation process

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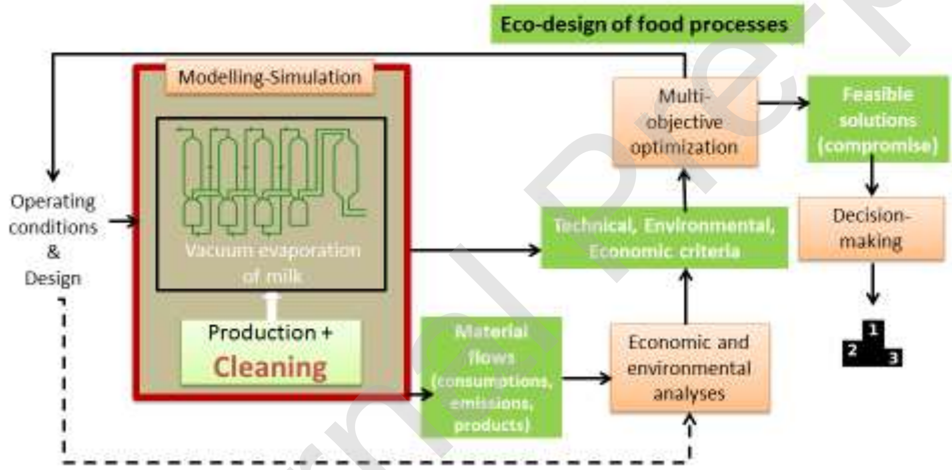
Graphical abstract



Highlights

- An eco-design approach was developed for an evaporator including cleaning and production phases
- Such an optimization produces improvements compared to industrial practices

- The cleaning phase contributed largely to the economic and environmental impacts of the process
- Research on cleaning kinetics is required to improve process performance of a dairy evaporator

Abstract

The cleaning phase is seldom included in the eco-design of food processes, since few cleaning kinetics models exist. The goal of this study was to investigate benefits of including a cleaning kinetics model, which considers three major operating parameters of cleaning (concentration, temperature and flow rate), in the eco-design of a food process. To this end, we developed an eco-design approach for a dairy evaporator process that includes both production and cleaning phases. A cleaning kinetics model was selected to predict cleaning duration as a function of the operating parameters of cleaning. Cleaning duration also depends on the fouling surface density, which depends on the duration of the production phase. Fouling surface density was predicted using three hypothetical fouling kinetics laws. After optimization, environmental and economic improvements were observed in process performance. The evaporation process is optimized at a high cleaning temperature (95°C), a flow-rate similar to that used during the production phase and a low caustic soda concentration (<2%). This study highlights that to optimize food processes in a more precise way, cleaning kinetics should be included and used to identify parameters that influence performance of the overall process.

Keywords

Eco-design; cleaning; kinetics; model; evaporation.

Nomenclature

A_i	Reduced variable (unitless)
Cp	Heat capacity (J.kg^{-1}.K^{-1})
D	Tube diameter (m)
H	Enthalpy rate (J.h^{-1})
k	Kinetic constant (s^{-1})
L^{vap}	Latent enthalpy of vaporization (MJ.kg^{-1})
$\dot{m}$	Mass flow rate (kg.h^{-1})
M_0	Fouling surface density (kg.m^{-2})
nt	Number of tubes in an evaporator effect (-)
r_F	Cleaning rate (kg.m^{-2})
ρ	Cleaning solution density (kg.m^{-3})
t	Time (s or h)
T	Temperature (°C or K)
v	Flow velocity (m.s^{-1}) with $v = \frac{\dot{m}}{3600\, \rho\, nt\, \pi \left(\frac{D}{2}\right)^2}$
X	Mass concentration (kg.kg^{-1})

1. Introduction

Cleaning-in-place (CIP) is commonly used in the food industry to ensure hygienic safety of foods and recover plant performance; however, it has high operating and investment costs (Tamime, 2009) and environmental impacts (Eide et al., 2003). This is particularly true in the dairy industry, which has long non-production periods dedicated to CIP (4-6 h per day) and a huge volume of effluents generated by CIP (50-95% of the volume of waste sent to the wastewater treatment facility, regardless of the type or size of the plant or equipment (Marty, 2001; Sage, 2005)).

Eco-design and optimization of food processing have attracted much attention in the past two decades (Stefanis et al., 1997; Banga et al., 2008; Erdogdu, 2008; Sharma et al., 2012). Ecodesign is an environmental management approach that aims at integrating environmental issues into the product development process, in order to improve the environmental performance of a product across its entire life cycle. However, the CIP procedure has rarely been considered. The literature indicates that three approaches have been used to address CIP in the eco-design of food processes, but none of them has included cleaning kinetics models, which represent the major operating parameters of cleaning:

- The first approach uses Life Cycle Assessment to identify the alternative CIP procedure with the lowest environmental impacts by comparing multiple CIP procedures (Eide and Ohlsson, 1998; Eide, 2002; Eide et al., 2003). This approach analyzes data of industrial CIP procedures, thus removing the need for predictive modeling of cleaning kinetics and excluding relationships between the production and cleaning phases.
- The second approach optimizes production scheduling (i.e. time management) while assuming a constant cleaning duration. For instance, Birewar and Grossmann (1989) minimized the duration of a production cycle in a multiproduct batch plant without considering the major operating conditions of cleaning or cleaning kinetics. They did, however, perform a sensitivity analysis of different scenarios of cleaning duration in an optimization strategy, as an initial step in predicting cleaning kinetics.
- The third approach uses a cleaning kinetics model to optimize costs and environmental impacts of production scheduling of batch plants. For example, Stefanis et al. (1997) appear to have used the model of Bird and Fryer (1991) to predict alkaline cleaning kinetics as a function of caustic soda concentration and initial fouling of the plant to optimize the eco-design of cheese production lines. This approach appears the most advanced, since it combines a model of cleaning kinetics with plant optimization. However, data on fouling thickness are excluded, and important cleaning parameters such as temperature and flow rate are not included as optimization variables.

The objective of this study was thus to investigate potential benefits of a comprehensive cleaning kinetics model that considers the influence of three major operating parameters of cleaning (concentration, temperature and flow rate) on the degree of fouling removal in the eco-design of a food process.

The process under study is a falling film evaporator that processes skim milk, which is especially relevant since evaporation, a widely used unit operation in the dairy industry, consumes large amounts of energy and generates large amounts of effluents. According to Ramirez et al. (2006), energy consumed during the evaporator cleaning phase can be as high as 70% of that of the production phase. Moreover, water consumed during the cleaning phase can represent 25-40% of that during the production phase (Bosworth et al., 2000).

The cleaning kinetics model used in this study was selected from those already described in the literature. To our knowledge, no specific study has focused on the mechanisms of cleaning or has modeled the cleaning kinetics of evaporators fouled by milk. Jeurnink and Brinkman (1994) empirically studied the cleaning of dairy evaporators, but current knowledge cannot quantitatively predict their fouling and cleaning. Several other studies seem suitable however, since they focus on predicting cleaning kinetics of thermal treatment equipment fouled by dairy deposits (Gallot-Lavallee et al., 1984; Bird and Fryer, 1991; Xin et al., 2002, 2004).

2. Materials and methods

2.1. Description of the process system

The system considered in this study consists of an evaporator system and the associated CIP station. For the purpose of the study, it is assumed that the CIP station is used only to clean the evaporator system. Hypotheses about the management and scheduling of production and cleaning are also used for the eco-design.

2.1.1. Evaporator

The equipment under study is an industrial tubular falling film evaporator. It runs 7 300 hours a year, of which 6 300 hours are production and 1 000 hours are downtime, which corresponds to cleaning and other operations related to production scheduling. All data on operating conditions and associated consumption came from the dairy industry. The evaporator processes 20 $t.h^{-1}$ of skim milk with 8.5% dry matter to produce concentrated milk with 47.7% dry matter. The standard duration of its production phase is 20 h. The evaporator is connected to pre-heaters, a pasteurizer and a condenser (confidential industry source). The evaporator has the following main characteristics:

- Four effects, in which milk is evaporated successively at 69.3, 64.2, 57.3 and 49.0°C. Condensates of each effect are used to pre-heat milk before pasteurization.
- A steam ejector recycles water vapor from the second effect, mixing it with 2 300 $kg.h^{-1}$ of steam to feed the first effect 6 049 $kg.h^{-1}$ of steam at 0.354 bar. Therefore, the evaporator consumes 2 300 $kg.h^{-1}$ of steam.

During the production phase, water is consumed by the condenser (16 739 $kg.h^{-1}$), and steam is consumed by the pasteurizer (464 $kg.h^{-1}$) and the evaporator. According to industrial practice (Cords et al., 2001), the evaporator is maintained under vacuum during cleaning, which means that both the evaporator and the CIP station consume steam and water during cleaning. Consequently, the evaporator was assumed to consume as much water and steam consumption during cleaning as during production (16 739 $kg.h^{-1}$ of water and 2 764 $kg.h^{-1}$ of steam).

2.1.2. Estimating fouling

Including the CIP procedure in the eco-design of the process requires information on the amount of fouling at the end of the production phase. More precisely, the efficiency and duration of cleaning depend on the amount of fouling to be removed (Xin et al., 2002). We did not consider changes in the nature of the fouling (i.e. composition and structure), although it can change depending on operating conditions of the production phase. Since no model can yet accurately predict the amount of fouling of an evaporator during production of milk concentrates, estimates or experimental data are necessary. Caric et al. (2009) reported a fouling surface density of 1.3 $kg.m^{-2}$ in a 4-effect evaporator after 20 h of processing whole milk, while Foster et al. (1989) demonstrated that skim milk produced the same amount of fouling as whole milk. Thus, we assumed that the surface density of fouling after 20 h of evaporation of skim milk equaled 1.3 $kg.m^{-2}$ (standard value).

To study the influence of the production phase on cleaning operating conditions, we used three arbitrary laws to estimate fouling surface density as a function of production times around 20 h: i) linear, ii) polynomial and iii) exponential (Table 1). The linear law corresponds to a 5% change in fouling surface density per hour before or after 20 h. The polynomial and exponential laws were used to simulate greater fouling due to highly concentrated and viscous products. Since industrial data indicated that production time ranges from 18-22 h, fouling was estimated for 18, 20 and 22 h (Table 1).

Table 1. Arbitrary estimates of fouling surface density (M_0) after 18, 20 and 22 h of evaporation time (t_{prod}), starting from the standard value of 1.3 $kg.m^{-2}$ at 20 h. Three fouling kinetics are considered: linear ($M_0 = 0.065 \times t_{prod}$), polynomial ($M_0 = -5 \times 10^{-5} + 0.0297 \times t_{prod} + 0.0018 \times (t_{prod})^2$) and exponential ($M_0 = 0.0311 \times \exp^{(0.1868 \times t_{prod})}$) with M in $kg.m^{-2}$ and t in h

Production time, t_{prod} (h)	**Fouling surface density ($kg.m^{-2}$)**		
	Linear	**Polynomial**	**Exponential**
18	1.17	1.10	0.90
20	1.30	1.30	1.30
22	1.43	1.50	1.90

2.1.3. CIP procedure

Analysis of industrial practices and the literature (Jeurnink and Brinkman, 1994; Bosworth et al., 2000; Goode et al., 2013) identified similarities among cleaning procedures. We used this information to define a standard cleaning procedure (Table 2) with five steps, each with specific operating conditions (temperature and concentration) and duration. For all steps, the flow rate was set at 130% of the production flow rate, following industrial practices (B. Colin, TGE S.A., pers. comm., 2016).

Given this standard cleaning procedure (Table 2), the standard production time (20 h) and yearly hours of production and downtime, a total of 314 cycles (i.e. production and cleaning) are run per year. As observed in the industry, when several production lines exist, especially when several evaporators are connected to a single spray dryer, scheduling constraints result in lag times. To represent the lag time between cycles, 80 min was added to the total cycle time, thus yielding a total standard cycle time of 1 390 min.

Table 2. Standard cleaning procedure for an industrial dairy evaporator fouled with skim milk (B. Colin, TGE S.A., pers. comm., 2016, and M. Dif, Elodys International, pers. comm., 2016)

No.	Step	Detergent	Temperature	Duration (min)
1	Pre-rinse	Water	Ambient	20
2	Alkali cleaning	Sodium hydroxide at 1.5%	75°C	30
3	Intermediate rinse	Water	Ambient	15
4	Acid cleaning	Nitric acid at 1.5%	60°C	30
5	Final rinse	Water	Ambient	15

2.1.4. The CIP station

The CIP station that produces the cleaning solutions consists of two simple unit operations:

1) mixing of water and chemical detergents to produce the cleaning solutions
2) heating of the cleaning solutions with steam (assumed efficiency: 80% - Martínez, 2017).

Both operations are considered continuous since only the duration of a given cleaning step is used to calculate consumption (i.e. water, steam, detergent). Electricity consumption of the CIP procedure was not considered, since little information on itis available, and CIP consumes only a small amount of electricity in dairy plants (less than 5%, according to Gugala et al. (2015)).

Since the CIP station is designed for single-use cleaning solutions, cleaning solutions and rinse water are discharged as wastewater immediately after use, which is the same practice used for industrial evaporators.

Steam consumption (corresponding to the steam flow rate $\dot{m}_{Steam}$ of the cleaning phase is calculated as:

$$\dot{m}_{Steam} = \frac{\dot{H}_{Solution}}{0.8 \times 10^{-6} L_{Water}^{Vap}} \quad (1)$$

where L_{Water}^{Vap} is the enthalpy of vaporization of water (at the steam temperature), and $\dot{H}_{Solution}$ the enthalpy rate required to heat the cleaning solutions.

Eq. 1 assumes total condensation of steam with the exchange of only latent heat. $\dot{H}_{Solution}$ is calculated as:

$$\dot{H}_{Solution} = \dot{m}_{Solution} \int_{T_1}^{T_2} Cp_{Solution} dT \quad (2)$$

where $\dot{m}_{Solution}$ is the flow rate of the cleaning solution, $Cp_{Solution}$ its heat capacity and T its temperature. T_1 and T_2 are respectively the ambient temperature (15°C) and the cleaning temperature of each step in the procedure (Table 2).

Eq. 2 uses empirical regressions of the heat capacity of caustic soda and nitric acid solutions (Eq. 3 and 4, respectively) from Aspen Plus software (Aspen Technology, 2011):

$$Cp_{Caustic\ soda} = 3228.49 - 4444.73 \times X_{NaOH} + 16.04 \times T \quad (3)$$

$$Cp_{Nitric\ acid\ solution} = 3190.06 - 3293.52 \times X_{Nitric\ acid} + 16.16 \times T \quad (4)$$

where X is detergent concentration (kg kg^{-1}).

2.2. Alkali cleaning kinetics model for an evaporator fouled by milk

2.2.1. Choice of the cleaning model

The cleaning model is used to predict the duration of alkali cleaning required to remove the deposit as a function of the major operating parameters of the cleaning (alkali concentration, temperature, flow rate). Many models have been developed, mainly for heat exchangers, to explain and/or predict the kinetics of removing dairy deposits. Gallot-Lavallee et al. (1984) (GL) developed a simple model of cleaning time as a function of cleaning parameters. The model of Bird and Fryer (1991) and Bird (1992) was the first to consider that the cleaning rate increases as sodium hydroxide concentration increases, up to the point that the concentration inhibits cleaning. Other studies also identified this behavior in dairy processes (Jeurnink and Brinkman, 1994; Lötscher et al., 1994), but no studies have included cleaning parameters in a model to predict the kinetic constants required to calculate the cleaning duration. More recently, long exposure to hot surfaces was identified to influence fouling characteristics (e.g. structure, thermal properties, chemical reactivity) (Ishiyama et al, 2011). This phenomenon, called “aging”, also decreases the cleaning rate, but is not yet included in predictions of cleaning duration. Xin et al. (2002, 2004) developed a model to predict removal kinetics of whey protein concentrate fouling using a variety of kinetic parameters identified from experimental data; however, their model did not relate kinetic parameters to cleaning parameters (concentration, temperature, flow rate) mathematically.

Thus, due to the lack of cleaning kinetic models that consider the most recent advances in cleaning knowledge, we selected the GL model for this study because it i) is the only one that estimates the cleaning kinetics constant as a function of concentration, temperature and flow rate; ii) requires a single parameter for fouling (i.e. initial surface density) and iii) does not require complex modeling of fouled equipment, which is desirable when optimizing processes at the factory level.

2.2.2. Description of the GL model and prediction of cleaning duration

The GL model predicts cleaning duration as a function of cleaning parameters (concentration, temperature, flow rate, fouling surface density). The model quantifies the kinetics of milk fouling removal with caustic soda as a kinetic constant *k* (s^{-1}), as follows:

$$log(k) = -1.01 + 0.27A_1 + 0.20A_2 + 0.16A_3 - 0.67M_0 \qquad (5)$$

where M_0 ($kg.m^{-2}$) is the fouling surface density, and A_1, A_2 and A_3 are reduced variables for the operating parameters of cleaning:

- Alkali solution temperature ($T\ in\ K$): $A_1 = (T - 273.15 - 75)/12$
- Sodium hydroxide concentration (X_{NaOH} in $kg.kg^{-1}$) $A_2 = (100X_{NaOH} - 2)/1.15$
- Alkali solution flow velocity (v in $m.s^{-1}$): $A_3 = (v - 1.1)/0.5$

Once the kinetic constant k is calculated, the cleaning rate (r_F) is calculated as a function of time (*t*):

$$r_F = M_0kte^{-kt} \qquad (6)$$

According to Bird and Fryer (Bird and Fryer, 1991; Bird, 1992), cleaning can be considered complete when, after reaching a maximum value, the cleaning rate decreases and reaches 2% of this maximum value. Complete cleaning time is thus the time at which this criterion is met. When tested with operating conditions of alkali cleaning in the standard procedure (75°C, 1.5% sodium hydroxide, 0.012 $m.s^{-1}$ flow velocity): the GL model predicted a cleaning duration of 24 min, which is similar to the 30 min of alkali cleaning used at the industrial scale. Although the model was developed for the cleaning of holding tubes, and since many hypotheses are potential sources of variation, the duration predicted is consistent with industrial practices.

2.3. Eco-design framework and key indicators for optimization

An optimization framework implemented in an Excel spreadsheet (Microsoft, Inc.) was used to eco-design the evaporator process including production and cleaning phases. Optimization entailed searching for optimal variables for alkali cleaning or the production phase to minimize or maximize one or several indicators. The variables were the following:

- Alkali solution concentration, 0.1-3.9% (boundaries of the GL model)
- Alkali solution temperature, 55-95°C (boundaries of the GL model)
- Alkali solution flow rate, 100-130% of production flow rates
- Production duration, 18, 20 or 22 h.
- Fouling kinetics law for the production phase, linear, polynomial or exponential (Table 1)

Indicators for both environmental and economic objectives were defined to perform the optimization. We considered three environmental indicators (i.e. consumption of steam, water, and sodium hydroxide) and two economic indicators (i.e. yearly production (concentrated milk produced per year) and gross profit (gross revenue minus the total cost of utilities and raw materials (i.e. milk, steam, water, detergents). Although milk evaporation is commonly used as a pre-concentration step before spray drying, gross revenue was related to the milk concentrate instead of the milk powder obtained by spray drying. Including milk powder in the boundaries of the system would have required estimating consumption and emissions of spray drying and packaging, which lay beyond the scope of this study. All indicators of costs and revenues were calculated on a yearly basis (Table 3).

Table 3. Costs of utilities and raw materials, and expected revenue from concentrated milk

Cost or revenue	Value
Steam (€.kg^{-1}) (confidential industry source)	0.032
Water (€.m^{-3}) (confidential industry source)	0.85
Caustic soda - 30% solution (€.t^{-1}) (M. Dif, Elodys International, pers. comm., 2016)	200
Nitric acid - 56% solution (€.t^{-1}) (M. Dif, Elodys International, pers. comm., 2016)	200
Raw milk - from producer (2014 mean, France) (€.kg^{-1}) (CNIEL, 2015)	0.355
50%-concentrated milk revenue (€.kg^{-1}) (CNIEL, 2015)	2.636

Two types of optimization of the evaporation system were performed:

- Single-objective optimization, which can be considered eco-design when the objective is to minimize an environmental indicator. We used Excel's Solver tool to minimize an indicator by changing design variables.
- Multi-objective optimization (MOO), in which several potentially conflicting objectives are considered. We used a genetic algorithm (*Multigen* code developed in a previous study (Gomez et al., 2010)) to produce Pareto-efficient alternatives and a multiple-criteria decision-making tool (M-TOPSIS, a variant of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) - Hwang and Yoon, 1981; Li et al., 2009; Mendoza et al., 2014) to rank the compromise solutions. The basic concept of M-TOPSIS is that the selected alternative lie closest to the "positive ideal solution" and farthest from the "negative ideal solution" in a geometrical sense. It was selected for its rational and understandable logic, and its straightforward calculation process (García-Cascales and Lamata, 2012). Each objective was given the same weight (i.e. 1).

2.4. Strategy of work

In this study, we first estimated the contribution of cleaning to the overall performance of the process to confirm that the cleaning phase has high costs and environmental impacts in the evaporation process. The estimation was performed

i) for the standard production and cleaning phases (Table 2) and

ii) for three production durations (18, 20 and 22 h) and three fouling levels and kinetics (Table 1).

We then optimized the process considering four objectives: minimizing consumption of steam, water, or sodium hydroxide, and maximizing gross profit.

i) First, the cleaning procedure was optimized based on a standard production duration to assess the influence of optimized cleaning procedures on the overall process.

ii) Next, the entire process was optimized (MOO) to obtain optimal indicator values based on production and cleaning parameters (cleaning concentration, temperature and flow rate, and production phase duration). Both single-objective and bi-objective optimization were performed using the three fouling kinetics laws. Thus, the production phase was included in the optimization procedure through the fouling kinetics laws.

3. Results and discussion

3.1. Contribution of cleaning to process performance

3.1.1. Contribution of cleaning to the standard production and cleaning phases

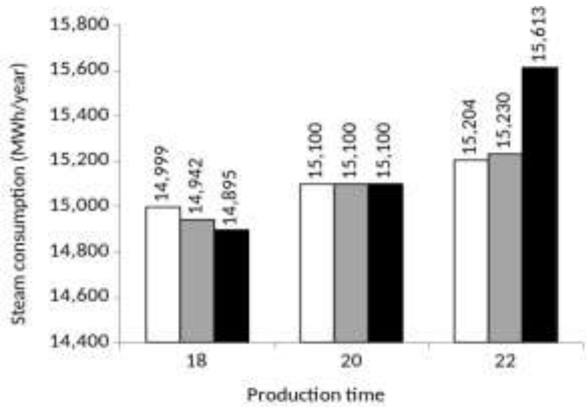
For standard procedures of the production phase (20 h) and cleaning phase (Table 2), the influence of the cleaning phase was not negligible compared to that of the production phase. Although cleaning took less time than production (110 min, i.e. 10% of production time), it consumed large amounts of steam and water and generated non-negligible environmental impacts: cleaning represented 15% (1 930 MWh.year^{-1}) of the production phase's steam consumption and up to 23% (24 000 m^3.year^{-1}) of its water consumption (Table 4). Thus, optimizing the evaporator process via the cleaning phase is challenging.

Table 4. Environmental and economic indicators for standard industrial production and cleaning parameters. Operating conditions for alkali cleaning: 1.5% mass concentration, 75°C, 130% of production flow rate, 1.30 kg.m^{-2} of fouling after 20h of produciton, 30 min of alkali cleaning.

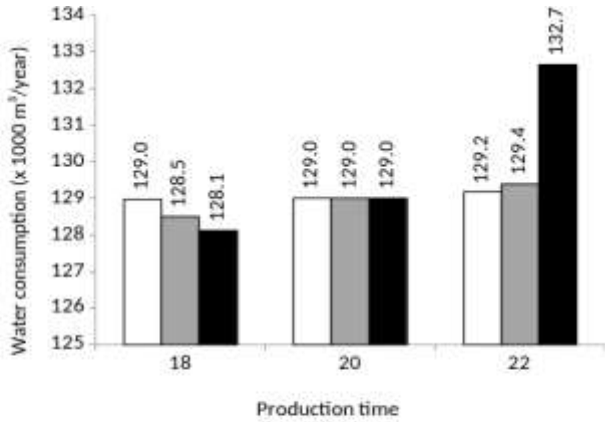
Indicator	Phase	Value
Number of cycles per year		314
Steam consumption (MWh.year^{-1})	Production	13 203
	Cleaning	1 930
Water consumption (10^3 m^3.year^{-1})	Production	105
	Cleaning	24
Sodium hydroxide consumption (t.year^{-1})	Cleaning	61
Yearly production (t.year^{-1})	Production	22 671
Gross profit (k€.year^{-1})	Production	14 416

3.1.2. Contribution of cleaning considering three fouling kinetics

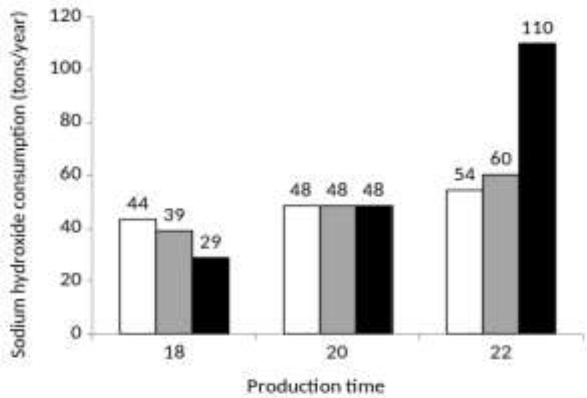
Predictions of the alkali cleaning duration required to remove fouling completely revealed the influence of production duration and fouling kinetics (Fig. 1).



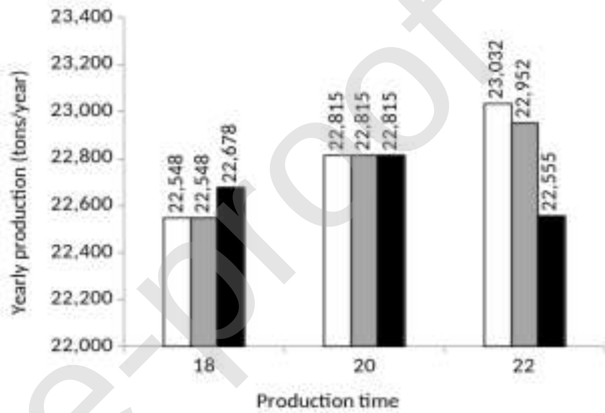
a) Steam consumption



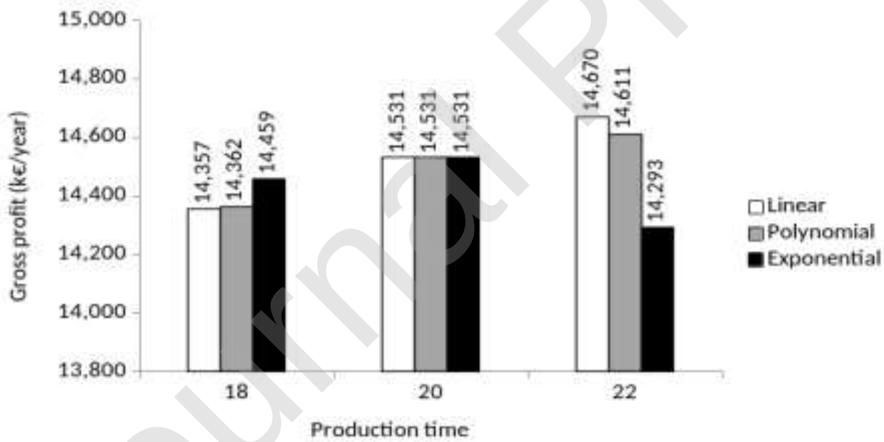
b) Water consumption



c) Sodium hydroxide consumption



d) Yearly milk concentrate production



e) Gross profit per year

Figure 1. Environmental and economic indicators for standard alkali cleaning parameters, variable production durations and three fouling kinetics. Numbers above histograms show indicator values at 18 and 22 h of production duration and those at 20 h.

The steam and water consumption of the cleaning phase represented a substantial percentage of the consumption of production (13-19% and 21-27%, respectively); however, the corresponding cleaning duration ranged from 13 (exponential kinetics after 18 h) to 60 minutes (exponential kinetics after 22 h) (Fig. 1). The longer the production duration, the longer the cleaning duration, which is consistent with longer production durations increasing the fouling surface density. After a production phase of 22 h, cleaning duration nearly doubled with exponential fouling kinetics (60 min) compared to linear and polynomial kinetics (29 and 32 min, respectively), whereas fouling surface density increased by only 26% and 32%, respectively. This indicates that for fluids with a high fouling potential (i.e. exponential fouling kinetics), cleaning duration must increase considerably (here, nearly double) if production duration increases by a few percentage points (10% of the standard duration), as observed in the dairy industry (M. Dif, Elodys International, pers. comm., 2016). As production duration (and thus cleaning duration) increased, steam, water and sodium hydroxide consumption increased (Fig. 1a-c). More resources were required to clean for longer periods. Overall, the environmental indicators followed the same trends as the hypotheses for cleaning duration and fouling kinetics: consumption of inputs increased as cleaning duration increased, and for a given production duration, it increased as fouling surface density increased. However, economic indicators followed different trends (Fig. 1d and e). For linear and polynomial fouling, yearly production of milk concentrate and gross profit increased with production duration, since more product was produced per year. Thus, the increase in yearly production compensated for the decrease in product output per production cycle, and consequently increased the yearly gross profit. For exponential fouling, both yearly production and gross profit were minimal for 22 h of production. Despite a longer production duration, the longer cleaning duration decreased the number of production cycles per year (i.e., from 314 to 284), thus producing less product per year. Gross profit followed the trend for yearly production closely because the product (i.e. milk concentrate) represented 98% of total costs, followed by steam (1.4%).

Thus, cleaning influenced overall system performance greatly when production duration changed. Since cleaning duration must adapt to the amount of fouling, the economic and environmental indicators follow different trends according to the fouling kinetics. Thus, it is necessary to understand fouling kinetics in the evaporator to adapt the cleaning procedure and to optimize the system. Since yearly production and gross profit followed similar trends as a function of production time and fouling kinetics (Fig. 1d and e), only gross profit was used in the subsequent optimization.

3.2. Optimization to eco-design the evaporator process

3.2.1. Optimization of cleaning procedure with the standard production duration

Regardless of the individual objective to be optimized (minimizing consumption of steam, water, or sodium hydroxide, or maximizing gross profit), optimal indicator values were obtained at the lowest flow rate (100%) and highest temperature (95°C) in the optimization framework (Table 5). Although one might expect the highest flow rate (130%) to increase performances (higher flow rate is known to decrease cleaning duration; Gallot-Lavallee et al. (1984)), the lowest flow rate compensated for the increase in cleaning duration by decreasing steam, water and NaOH consumption. Similarly, the highest temperature yielded the highest overall performance, since yearly costs were lower despite the need for more heating power. The remaining cleaning parameter – concentration – was the most relevant parameter for optimizing the process.

Table 5. Single-objective optimization of the evaporator process using the standard production phase (production duration: 20h; Fouling surface density: 1.30 kg.m^{-2}). Optimized cleaning operating parameters are shown along with indicator values. Values with positive and negative signs represent differences from the standard industrial practice.
NaOH = sodium hydroxide

		Standard industrial practice	Optimization objectives			
			Minimize steam cons.	Minimize water cons.	Minimize NaOH cons.	Maximize gross profit
Optimized cleaning parameters	Concentration (% mass)	1.5%	3.9%	3.9%	0.1%	3.9%
	Temperature (°C)	75	95	95	95	95
	Flow rate (% production rate)	130	100	100	100	100
Indicators and key variables	Alkali cleaning time (min)	30	3	3	15	3
	Number of cycles per year	314	320 +6	320 +6	318 +4	320 +6
	Steam consumption (MWh.year^{-1})	15 133	14 749 -384	14 749 -384	14 973 -161	14 749 -384
	Water consumption (10^3 m^3.year^{-1})	129.6	125.9 -3.7	125.9 -3.7	127.4 -2.2	125.9 -3.7
	NaOH consumption (t.year^{-1})	61	13 -48	13 -48	2 -60	13 -48
	Yearly production (t.year^{-1})	22 671	23 104 +433	23 104 +433	22 960 +289	23 104 +433
	Gross profit (k€.year^{-1})	14 416	14 765 +349	14 765 +349	14 666 +249	14 765 +349

Regardless of the individual objective optimized, single-objective optimization resulted in substantially shorter cleaning durations, which improved the environmental and economic indicators (Table 5). Steam and water consumption decreased by 2.5% and 2.8%, respectively, resulting in a 2.4% increase in gross profit, which corresponds to an absolute increase of 349 k€ per year. The largest improvement was obtained when minimizing sodium hydroxide consumption, which decreased by more than 90% (from 61 to 2 t.year^{-1}).

These results indicate that including a cleaning kinetics model in optimization can improve overall process performance greatly and can also help identify operating parameters to which process performance is more sensitive. These results also demonstrate that for the evaporator system and under the restrictions of this study, i) maximizing gross profit and minimizing water and steam consumption are consistent (non-antagonistic) objectives, but ii) minimizing sodium hydroxide consumption is antagonistic to the other three objectives. Consequently, MOO was performed with two objectives: minimize sodium hydroxide consumption and maximize gross profit. The genetic algorithm generated 10 Pareto-optimal alternatives (Fig. 2). Sodium hydroxide consumption varied greatly (1.6-13.4 $t.year^{-1}$), but 8 of the alternatives had a similar increase in gross profit compared to the standard case (ca. 2%). If a decision-maker were to consider that these 8 alternatives provided essentially the same gross profit, then all alternatives except the one with the lowest sodium hydroxide consumption would be removed from the decision-making process. Without information from a decision-maker, however, we kept all 8 alternatives for ranking.

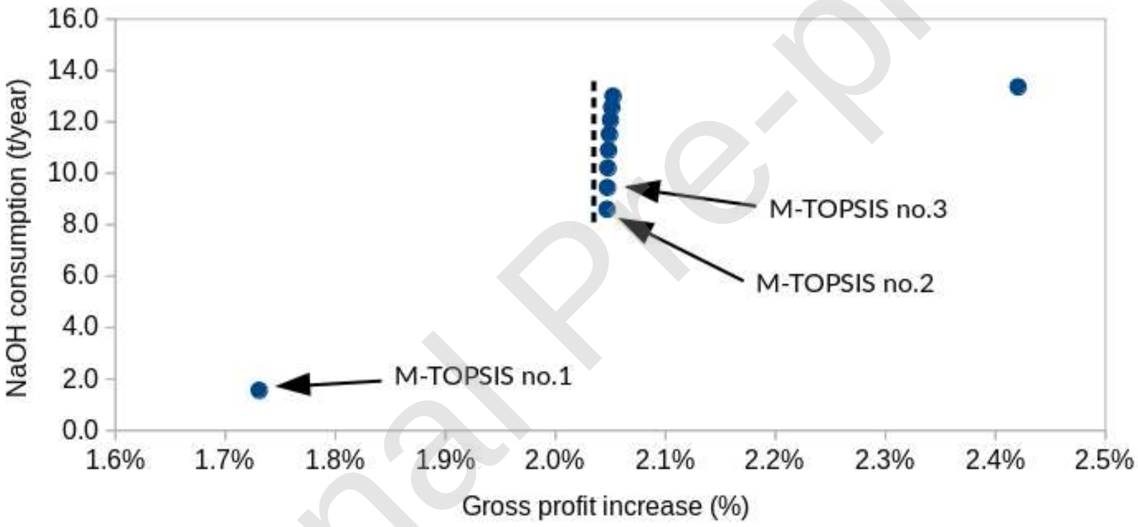


Figure 2. Pareto front for bi-objective optimization of the evaporator system based on the standard production procedure. Arrows identify the top three alternatives according to M-TOPSIS ranking.

Among the three best alternatives predicted by the M-TOPSIS method, the best alternative corresponded to the minimum sodium hydroxide consumption (Tables 5 and 6). For MOO, one could have expected a top-ranked solution with intermediate sodium hydroxide consumption, since the best alternatives represented trade-offs between objectives. Because of how M-TOPSIS ranks alternatives, however, the objective with greater improvements (>80% decrease in sodium hydroxide consumption, rather than a ca. 2% increase in gross profit) had a higher rank. The other two best alternatives included higher sodium hydroxide consumption (0.7% and 0.8%, respectively) and a higher gross profit than the best M-TOPSIS alternative (Table 6).

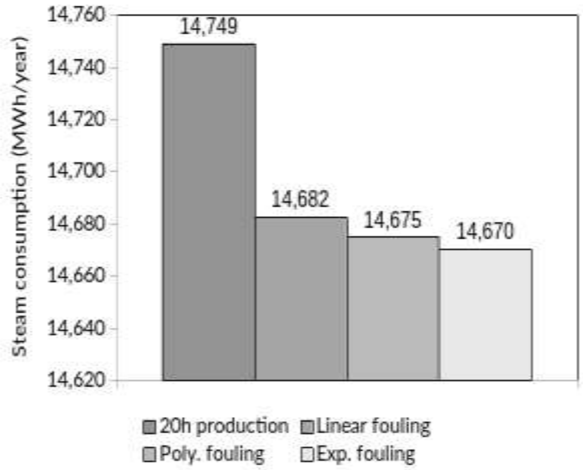
Table 6. Top three Pareto-optimal alternatives according to the M-TOPSIS method for bi-objective optimization of the evaporator process with 20 h of production duration. Both objectives have the same weight (1).

	Parameter or variable	M-TOPSIS no.1	M-TOPSIS no. 2	M-TOPSIS no. 3
Optimized parameters	Concentration (% mass)	0.1%	0.7%	0.8%
	Temperature (°C)	95	95	95
	Flow rate (% production rate)	100	100	100
Indicators and miscellaneous variables	Alkali cleaning time (min)	15	12	11
	Number of cycles per year	318	319	319
	Steam consumption ($MWh.year^{-1}$)	14 973	14 934	14 921
	Water consumption (10^3 $m^3.year^{-1}$)	127.4	127.2	127.1
	Sodium hydroxide consumption ($t.year^{-1}$)	1.6	8.7	9.5
	Yearly production ($t.year^{-1}$)	22 960	23 032	23 032
	Gross profit ($k€.year^{-1}$)	14 666	14 711	14 711
	Gross profit increase (%)	1.73	2.05	2.05

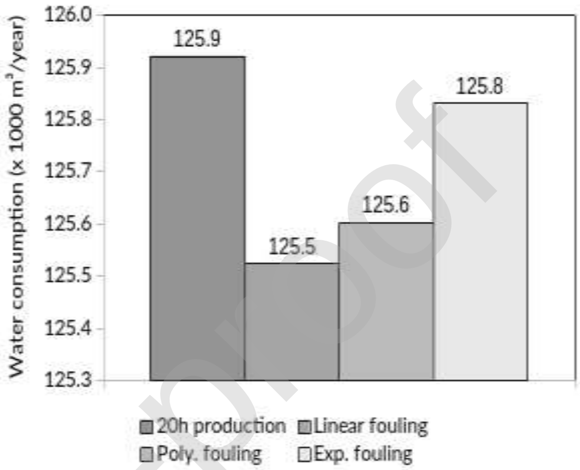
The optimization framework helped identify potential increases in process performance. Among all optimizations, improvements in industrial practice were as high as 97% for sodium hydroxide consumption, 2.5% for steam consumption, 2.8% for water consumption and 2.4% for gross profit (Tables 5 and 6). The cleaning operating parameters corresponding to these improvements differ significantly from those used in standard industrial practice, which demonstrates the benefits of including the cleaning phase in process optimization and eco-design.

3.2.2. Optimization of the entire evaporator process considering production and cleaning phases

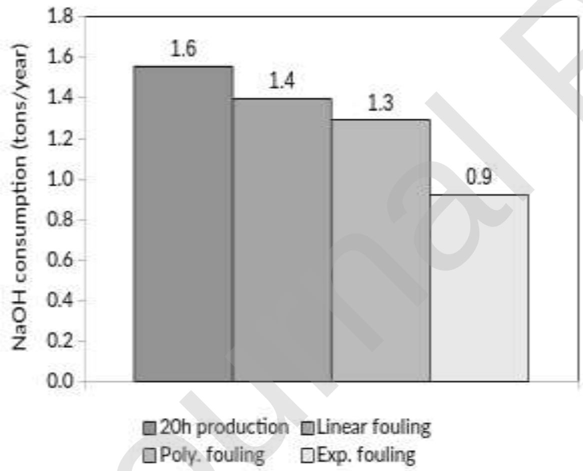
The optimal values of the four economic and environmental indicators varied after single-objective optimization (Fig. 3). See Table S1 (Supplementary materials) for values of indicators and optimized operating parameters.



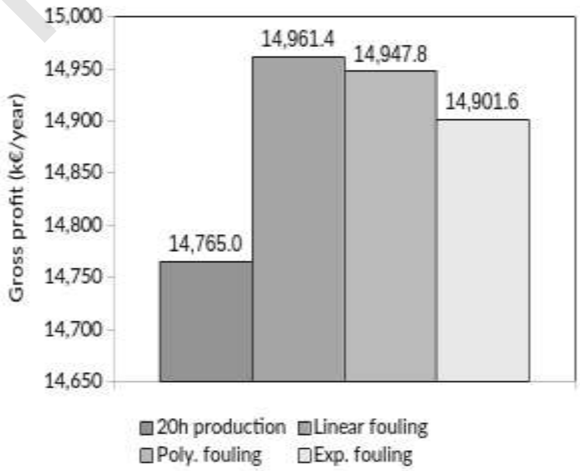
a) Steam consumption



b) Water consumption



c) Sodium hydroxide consumption



d) Gross profit per year

Figure 3. Optimal environmental and economic indicators as a function of fouling kinetics laws (linear, polynomial and exponential). The "20h production duration" corresponds to single-objective optimization of the cleaning phase.

Including both cleaning and production phases in the optimization procedure improved indicators compared to optimizing only the cleaning phase with a fixed duration of 20 h, regardless of the fouling kinetics law used (Fig. 3). Steam and water consumption decreased by less than 1%, while sodium hydroxide consumption decreased by 41% (with exponential fouling), and gross profit increased by ca. 1% (137-196 k€) for all laws used.

Optimal production durations can be identified, while how much the fouling kinetics law influences process performance is a function of production duration. To minimize steam consumption and sodium hydroxide consumption, the optimal production duration was ca. 18 h, with the hypothesis that exponential fouling kinetics minimize consumption of the three inputs. To minimize water consumption (except with exponential fouling) and maximize gross profit, the optimal production duration was ca. 22 h.

Results of bi-objective optimization and M-TOPSIS ranking of the fouling kinetics laws showed that the trade-off always combined the lowest detergent concentration (much lower than the maximum 2% sodium hydroxide concentration determined by Bird and Fryer (1991) and Bird (1992)), the highest temperature and the lowest (or nearly so) flow rate, as observed with a 20 h production duration (Table 7). Although an optimized production duration tended to have higher consumption, gross profit increased by 1% with linear fouling, which represents a 2.8% increase compared to the standard industrial case. Thus, to optimize gross profit, it seems appropriate to include production duration among optimization variables. Doing so also widens the range of possible operating parameters for cleaning and production, and thus widens the possible trade-offs when optimizing the process.

Table 7. Bi-objective optimization results as a function of fouling kinetics law with the standard industrial case and with bi-objective optimization for 20 h of production duration.

	Standard industrial case	M-TOPSIS no. 1 with 20 h production duration	Fouling kinetics law used with M-TOPSIS no. 1		
			Linear	Polynomial	Exponential
Production duration (h)	20	20	22.0	21.9	20.3
Concentration (% mass)	1.5%	0.1%	0.1%	0.1%	0.1%
Temperature (°C)	75	95	95	95	95
Flow rate (% production rate)	130	100	100	100	101
Alkali cleaning time (min)	30	15	18	21	17
Number of cycles per year	314	318	292	292	313
Steam consumption ($MWh.year^{-1}$)	15 133	14 973	15 054	15 091	15 025
Water consumption ($.10^3$ $m^3.year^{-1}$)	129.6	127.4	127.3	127.5	127.6
Sodium hydroxide consumption ($t.year^{-1}$)	61	1.6	1.7	2.0	1.8
Yearly production ($t.year^{-1}$)	22 671	22 960	23 185	23 135	22 987
Gross profit ($k€.year^{-1}$)	14 416	14 666	14 815	14 780	14 682

Optimization of cleaning and production phase parameters reveals the existence of optimal operating conditions, which can result in better overall process performance than optimizing only cleaning. Eco-design of the evaporator process thus benefits from including cleaning and fouling kinetics in the MOO framework.

4. Conclusion

This study developed an eco-design approach for a dairy evaporation process that combines a cleaning kinetics model and fouling kinetics hypotheses. Results indicate that considering both cleaning and production phases when optimizing the evaporator process can result in improvements compared to both industrial practices, even with uncertainty in fouling kinetics. Doing so can also help estimate potential economic savings and reduction in environmental impacts. The evaporation process was optimized at a high cleaning temperature (95°C), a flow rate similar to that used during the production phase and a low detergent concentration (<2%). These improvements can also be applied with little to no investment, since cleaning parameters (concentration, temperature, flow rate) and production duration influence mainly (if not only) the operation of the process. Before these improvements are implemented, however, the eco-design approach could be developed further by considering recent advances in modeling the cleaning process using computer fluid dynamics (e.g. Joppa et al. (2016)), along with deeper knowledge of cleaning kinetics to predict process performance accurately. Special attention should be paid to the establishment and integration of cleaning model assuming non linear influence with NaOH concentration.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

CNIEL - Centre National Interprofessionnel de l'Economie Laitière (2015). L'économie laitière en chiffres - Edition 2015. URL: http://fr.calameo.com/books/002230051347964ef558f

Banga, J. R., Balsa-Canto, E. and Alonso, A. A. (2008). Quality and Safety Models and Optimization as Part of Computer-Integrated Manufacturing, Comprehensive Reviews in Food Science and Food Safety 7(1), 168-174.

Bird, M. R. (1992). Cleaning of food process plant. Ph.D. thesis, University of Cambridge.

Bird, M. R. and Fryer, P. J. (1991). Experimental study of the cleaning of surfaces fouled by whey proteins, Food and Bioproducts Processing 69(1), 13-21.

Birewar, D. B. and Grossmann, I. E. (1989). Incorporating scheduling in the optimal design of multiproduct batch plants, Computers & Chemical Engineering 13(1), 141-161.

Bosworth, M. E. D., Hummelmose, B. and Christiansen, K. (2000). Cleaner production assessment in dairy processing. Technical report, COWI Consulting Engineers and Planners AS, Denmark.

Caric, M., Milanovic, S., Akkerman, C., Kentish, S. and Tamime, A. (2009). Technology of evaporators, membrane processing and dryers. In: Dairy Powders & Concentrated Products, Wiley VCH, Chichester, UK.

Cords, B., Dychdala, G. and Richter, F. (2001). Cleaning and sanitizing in milk production and processing. In: (Ed.), Applied dairy microbiology, Second Ed., Marcel Dekker, Inc..

Eide, M. (2002). Life cycle assessment (LCA) of industrial milk production, The International Journal of Life Cycle Assessment 7(2), 115-126.

Eide, M. H., Homleid, J. P. and Mattsson, B. (2003). Life cycle assessment (LCA) of cleaning-in-place processes in dairies, LWT - Food Science and Technology 36(3), 303 - 314.

Eide, M. H. and Ohlsson, T. (1998). A comparison of two different approaches to inventory analysis of dairies, The International Journal of Life Cycle Assessment 3(4), 209-215.

Erdoğdu, F., 2008. Optimization in food engineering. CRC Press.

Foster, C. L., Britten, M. and Green, M. L. (1989). A model heat-exchange apparatus for the investigation of fouling of stainless steel surfaces by milk I. Deposit formation at 100 C, Journal of Dairy Research 56(2), 201-209.

Gallot-Lavallee, T., Lalande, M. and Corrieu, G. (1984). Cleaning Kinetics Modeling of Holding Tubes Fouled During Milk Pasteurization1, Journal of Food Process Engineering 7(2), 123-142.

Garcia-Cascales, M. S. and Lamata, M. T. (2012). On rank reversal and TOPSIS method, Mathematical and Computer Modelling 56(5), 123-132.

Gomez, A., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., Latgé, C. and Haubensack, D. (2010). Multiobjective genetic algorithm strategies for electricity production from generation IV nuclear technology, Energy Conversion and Management 51(4), 859-871.

Goode, K. R., Asteriadou, K., Robbins, P. T. and Fryer, P. J. (2013). Fouling and cleaning studies in the food and beverage industry classified by cleaning type, Comprehensive reviews in food science and food safety 12(2), 121-143.

Gugala, M., Zarzecka, K., Kapela, K. and Sikorska, A. (2015). Analysis of Energy Consumption in the Facilities of the Ciechanów Dairy Cooperative, Journal of Ecological Engineering 16(3).

Hwang, C.-L. and Yoon, K. (1981). Methods for multiple attribute decision making. In: Multiple attribute decision making, Springer.

Ishiyama, E. M., Paterson, W. R., & Ian Wilson, D. (2011). Optimum cleaning cycles for heat transfer equipment undergoing fouling and ageing. Chemical Engineering Science, 66(4), 604-612.

Jeurnink, T. J. M. and Brinkman, D. W. (1994). The cleaning of heat exchangers and evaporators after processing milk or whey, International Dairy Journal 4(4), 347 - 368.

Joppa, M., Köhler, H., Rüdiger, F., Majschak, J.-P., & Fröhlich, J. (2017). Experiments and Simulations on the Cleaning of a Swellable Soil in Plane Channel Flow. Heat Transfer Engineering, 38(7-8), 786-795.

Li, C., Zhang, X., Zhang, S. and Suzuki, K. (2009). Environmentally conscious design of chemical processes and products: Multi-optimization method, Chemical Engineering Research and Design 87(2), 233-243.

Lötscher, D., Henck, M., and Gallmann, P. (1994). Höhere Dosis reinigt weder besser noch schneller. Deutsche Milchwirtschaft 45(17), 783-784.

Martínez, I. (2017). Heat Exchangers, Lectures on Heat and Mass Transfer.

Marty, P. (2001). Maîtrise de la consommation d'eau dans les industries agro-alimentaires, Industries alimentaires et agricoles 118(5), 35-39.

Mendoza, L.-F. M., Boix, M., Azzaro-Pantel, C., Montastruc, L. and Domenech, S. (2014). Biodiesel production from waste vegetable oils: combining process modelling, multiobjective optimization and life cycle assessment (LCA), Computer Aided Chemical Engineering, 235-240.

Ramirez, C. A., Patel, M. and Blok, K. (2006). From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry, Energy 31(12), 1984 - 2004.

Sage, M. (2005). Valorisation des eaux de procédés de l'industrie laitière en méthanisation et dénitrification. PhD thesis, École Nationale Supérieure d'Agronomie de Rennes, France.

Sharma, S., Rangaiah, G. P. and Cheah, K. S. (2012). Multi-objective optimization using MS Excel with an application to design of a falling-film evaporator system, Food and Bioproducts Processing 90(2), 123 - 134.

Stefanis, S., Livingston, A. and Pistikopoulos, E. (1997). Environmental impact considerations in the optimal design and scheduling of batch processes, Computers & chemical engineering 21(10), 1073-1094.

Tamime, A. Y., 2009. Cleaning-in-place: dairy, food and beverage operations. John Wiley & Sons. Chichester, UK.

Xin, H., Chen, X. and Özkan, N. (2002). Cleaning rate in the uniform cleaning stage for whey protein gel deposits, Food and bioproducts processing 80(4), 240-246.

Xin, H., Chen, X. D. and Özkan, N. (2004). Removal of a model protein foulant from metal surfaces, AIChE journal 50(8), 1961-1973.

Supplementary materials

Table S1. Single-objective optimization results with production duration as a design variable, by fouling kinetics law

		Optimization objectives Minimize steam consumption			Minimize water consumption			Minimize sodium hydroxide consumption			Maximize gross profit		
	Fouling kinetics law	Linear	Poly.	Exp.	Linear	Poly.	Exp.	Linear	Poly.	Exp.	Linear	Poly.	Exp.
Optimized parameters	Production duration (h)	18.04	18.05	18.23	21.97	21.55	19.77	18.02	18.00	18.00	21.90	21.88	21.83
	Concentration (% mass)	3.7%	3.9%	3.8%	3.8%	3.9%	3.8%	0.1%	0.1%	0.1%	3.9%	3.9%	3.9%
	Temperature (°C)	94	95	94	95	95	95	95	95	95	95	95	95
	Flow rate (% production rate)	100	100	100	100	101	100	100	100	100	100	100	100
Indicators and miscellaneous variables	Alkali cleaning time (min)	3	2	2	4	4	3	12	11	8	4	4	7
	Number of cycles per year	350	350	347	294	299	323	348	349	350	296	296	296
	Steam consumption (MWh.year^{-1})	14 682	14 675	14 670	14 787	14 781	14 728	14 859	14 857	14 804	14 842	14 845	14 883
	Water consumption (10^3 m^3.year^{-1})	126	126	126	126	126	126	127	127	127	126	126	126
	Sodium hydroxide consumption (t.year^{-1})	13.0	11.1	8.9	15.2	16.5	12.6	1.4	1.3	0.9	14.9	17.1	28.2
	Yearly production (t.year^{-1})	22 792	22 806	22 841	23 315	23 261	23 052	22 640	22 678	22 743	23 401	23 384	23 328
	Gross profit (k€.year^{-1})	14 556	14 567	14 592	14 906	14 869	14 731	14 454	14 479	14 526	14 961	14 948	14 902