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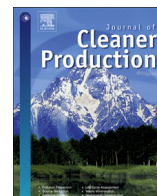
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Comparing economic and environmental performance of three industrial cheesemaking processes through a predictive analysis

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ABSTRACT

The From'Innov cheesemaking process was recently suggested to increase process control and flexibility while reducing the use of energy and fresh water. It focuses on building cheese texture and aroma separately, in a shorter time than any other cheese technology, by enriching a liquid precheese with aromatic matrices fermented by traditional ripening microorganisms. This study assesses the economic benefits, and the use of energy and fresh water of the From'Innov process through predictive analysis. A singleday production of industrial bloomy soft cheese (Camembert-type) was simulated in three distinct virtual plants (100,000 kg of milk per day) using different technological approaches: the From'Innov, the Maubois-Mocquot-Vassal (MMV, another liquid pre-cheese process) or the traditional processes. With its higher margin and its lower specific energy and fresh water consumption, the From'Innov process appeared to be the most efficient.

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1. Introduction

Cheese is one of the most consumed dairy products in the world and its global market has increased by 9.9% since 2010 (International Dairy Federation, 2016). However, the cheesemaking industry is also facing a major challenge: the need to reduce its environmental footprint. The production of raw milk is a major contributor to that environmental impact (Milani et al., 2011), but it is important to note that there are many reasons why cheese is one of the most energy-demanding dairy products to make (Xu et al., 2009). One reason is that the traditional cheesemaking process converts only a small fraction of the milk to curd (around 10% w.w.⁻¹, depending on the cheese variety [Fox et al., 2017]) and generates large volumes of by-product (whey) that still contains highly valuable proteins and dry matter (Maubois, 2018). Not only

is this process energy-demanding, but it also consumes a large volume of fresh water (1.2–3.8 L of water per L of milk processed [Korsström and Lampi, 2001]) to ensure a sanitary processing environment, finally leading to a significant volume of wastewater (0.9 ± 0.54 L per L of milk processed) (Danalewich et al., 1998). Cheese manufacture may also involve long ripening times (several days to months [Fox et al., 2017]) which requires facilities with a large surface area for ripening and high cooling energy demands to maintain a temperature generally close to 12 °C. Valorization of the by-products and waste volume reduction through membrane filtration can help lower the environmental impact of cheese (Milani et al., 2011). However, an alternative technology which would both manufacture a curd with a higher dry matter recovery and reduce the consumption of natural resources would be of great interest (Castanheira et al., 2006).

Several decades ago, a new cheesemaking process named after its inventors, the Maubois-Mocquot-Vassal or MMV process was developed with that vision (Maubois et al., 1969). Instead of draining the curd in a vat, as for the traditional cheesemaking process, the MMV process concentrates the milk by ultrafiltration (UF) prior to the cheesemaking process (Maubois et al., 1971). In

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other words, UF is performed until the milk reaches a total solids (TS) content equal to that of the cheese target. The retentate obtained, also known as “liquid pre-cheese”, is then coagulated with rennet in an unperforated mold. This process generates an unincubated by-product (UF permeate), with a lower biochemical oxygen demand (BOD) and chemical oxygen demand (COD) than traditional whey (El-Tanboly et al., 2017). Indeed, it has a more stable and constant composition throughout the year, as well as throughout the production day since it is not subjected to acidification, as is whey. It is also free of cheese fines, fat, rennet, lactic acid bacteria (LAB), caseinomacropptide (CMP) and colorant (Ardisson-Korat and Rizvi, 2004). The MMV process increases protein recovery in the cheese (more than 98%, depending on the protein permeability of the UF membrane) and reduces the amount of inputs (starter cultures and rennet, by 80%) (Maubois et al., 1971). Moreover, it does not require specialized cheese makers, which facilitates recruitment of employees. MMV cheeses can generate defects such as acid taste (Brulé et al., 1974) or sandy textures (Maubois, 1979) if the calcium content of the retentate is not adjusted (Brulé et al., 1975). They are also known to ripen slowly due to inhibition of proteolysis (Green et al., 1981).

The From'Innov process was recently developed to solve the ripening issues of the MMV process by building cheese texture and aroma separately (Garric et al., 2016). According to this process, aromatic matrices are prepared in bioreactors through the fermentation of different dairy media such as milk, cream or whey by traditional cheese ripening microorganisms. These aromatic matrices are added to the liquid pre-cheese prior to its coagulation. Since the aromas are already in the cheese, its ripening time is significantly reduced or even unneeded, depending on the type of cheese produced. In fact, for bloomy soft cheeses such as Camembert, a ripening of short duration may be performed, but only for esthetic purposes (i.e., for the growth of white moulds such as *Penicillium camemberti* and/or *Geotrichum candidum* on cheese rind).

Compared to the traditional and MMV processes, the From'Innov approach provides opportunities to improve the efficiency of the cheesemaking process. It offers increased production yield (higher protein recovery in the cheese as in MMV process), shorter ripening time and a lower labour requirement which, together, could significantly decrease operational costs. Consequently, the major objectives of this study were to evaluate the economic viability of the From'Innov process using a predictive model designed for this study, and to compare the energy and fresh water consumption of this process to that of the MMV and traditional processes for the production of a Camembert-type bloomy soft cheese in three distinct virtual plants.

2. Materials and methods

The predictive analysis of the three technological itineraries were performed assuming 100,000 kg of whole raw milk (12.9% w.w⁻¹ of TS, 4.4% w.w⁻¹ of lactose, 3.9% w.w⁻¹ of fat, 3.4% w.w⁻¹ of proteins and 0.8% w.w⁻¹ of ashes [Bylund, 2003]) received daily at three different virtual plants. The results were compared using the same functional unit: the production of 10,000 kg of Camembert cheese (bloomy soft cheese, cylindrical shape, diameter of 10.5 cm, and height of 3 cm, 250 g) produced in a French plant operating 260 d per year. At the end of ripening, the cheeses generated by the three virtual plants had a similar chemical composition: 47.1 ± 0.5% total solids (TS), and 1.5 ± 0.1% salt in water ratio (SW) (Mietton and Chablain, 2018). Due to the high protein content of the liquid pre-cheeses, the cheeses had a fat content in dry solids basis (FDS) of 46.1 ± 0.5% and 67.7 ± 0.5% of moisture in a fat-free basis (MFFB), which are lower than industry targets.

2.1. System boundaries

The system boundaries were limited to the cheesemaking processes, from receiving the raw milk at the plant entry-gate to the cheese storage prior to leaving the plant exit-gate (gate-to-gate boundary) (Fig. 1). The environmental impacts of inputs such as the raw milk, or those associated with the end of the cheese lifecycle were ignored since they do not differ between the different processes.

2.2. Plant design

Plans of the virtual plants were drawn (Appendices A, B and C, Figures A1, A2, A3, B1 and C1) in order to estimate the required surface area of the production, ripening and packaging facilities, and the pipe lengths needed to transport dairy fluids and CIP solutions. Plans of the ripening and packaging areas of the MMV and the From'Innov plants were not provided since they only differ in size compared to the traditional plant, but the sizes were provided in Appendix D (Table D.1). The ripening area included a storage room to store the clean ripening materials (ripening racks). The ripening rooms were sufficiently large to store one day of production. Their size depended on the production yield of each process. Raw milk, UF permeate and whey were stored in 50,000 L tanks outside the plants.

2.3. Description of the three cheesemaking processes

For the three scenarios, the cheesemaking process starts with the reception of deaerated raw milk. The milk is pumped into two silos and stored at a temperature below 6 °C for a mean duration of 16 h. The tanks are agitated once per hour at a speed of 24 rpm (Paludetti et al., 2018) for 2 min (Goodridge et al., 2004).

2.3.1. Description of the traditional process

During the traditional process, the fat and protein contents of the cheese milk must be standardized with cream (45% fat w.w⁻¹) and UF skim milk concentrate at a mass concentration factor (MCF) of 3X (10.3% protein w.w⁻¹). Cream and skim milk concentrate are generated at the plant. The milk is pasteurized at 78 °C (15 s) and skimmed (50 °C) at a flow rate of 12,000 kg h⁻¹. Throughout the pasteurization process, the energy of the pasteurized milk is recovered by the plate heat exchanger (PHE) to preheat the raw milk, and cool the pasteurized milk at 12 °C (regenerative efficiency of 88%). At the flow rate considered, the volume of skim milk needed to prepare the skim milk concentrate is obtained in 2.90 h. The fat separator is then virtually switched off, and the remaining pasteurized whole milk is pumped into two standardization tanks. The cream recovered from the skimming process is cooled at 12 °C in another PHE. One fraction is pumped into the standardization tank to complete the fat standardization, while the other fraction (2,203 kg) is sold as fresh cream. Following UF, the 3× retentate generated at 50 °C is cooled at 12 °C and pumped into the standardization tanks to obtain a protein to fat ratio of 1.22. The standardized milk is inoculated with a mesophilic starter culture prior to cold maturation at 12 °C for 16 h. The next day, the standardized milk is pasteurized again at 78 °C (15 s), cooled at 35 °C and pumped into the warm maturation tanks where it is enriched in calcium chloride and inoculated with lyophilized cultures of thermophilic lactic acid bacteria (0.002% w.w⁻¹) and ripening microorganisms (*P. candidum*, *G. candidum* and yeasts, total of 0.0005% w.w⁻¹). The four 2500 L tanks are inoculated at 20 min intervals. Following a warm maturation, the milk is renneted in-line during its transfer into 230 L vats circulating on a conveyor (continuous process). The resulting gel is mechanically cut after 40 min and matured for

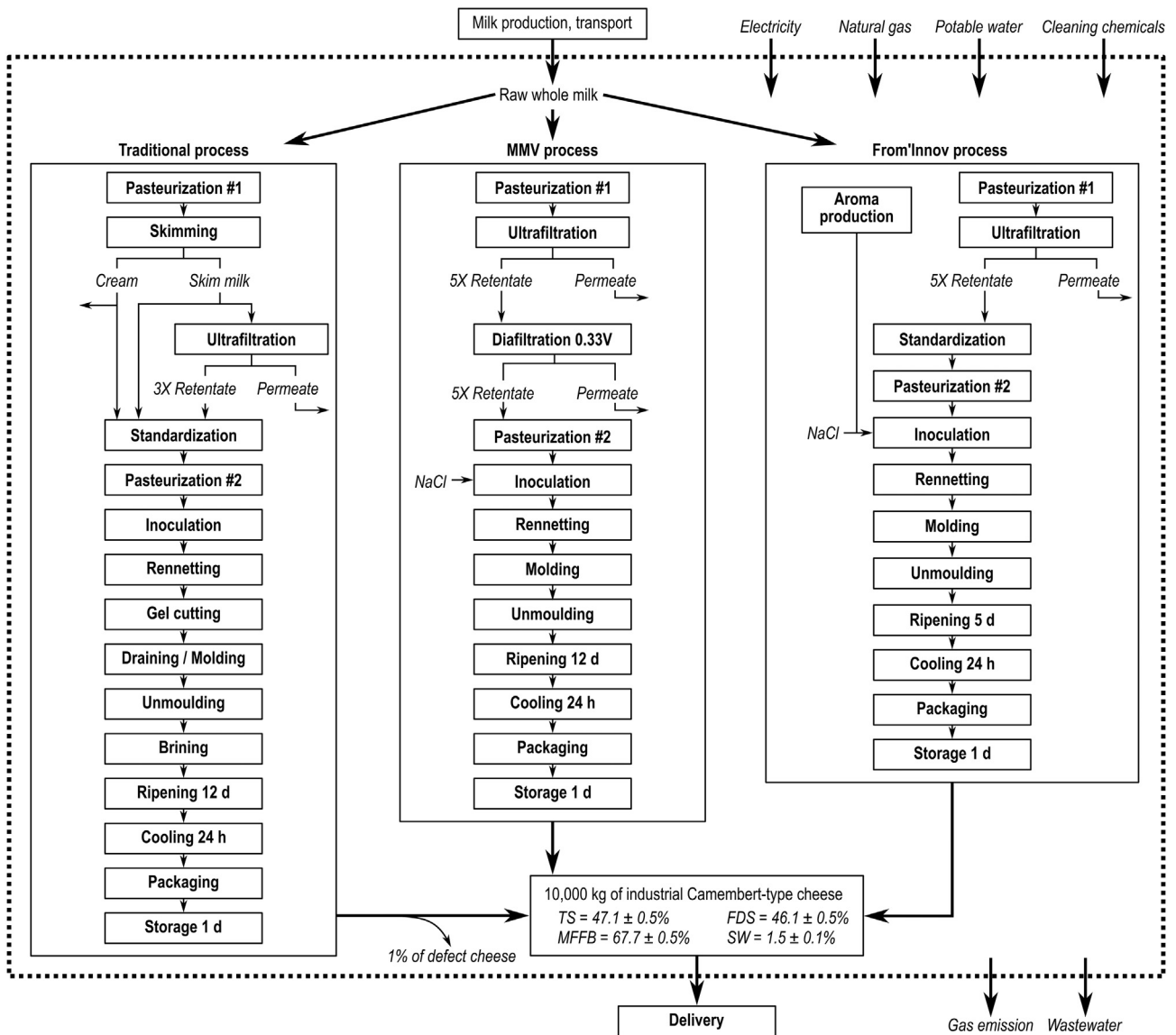


Fig. 1. System boundaries and technological approaches for the production of 10,000 kg of industrial Camembert-type soft cheese at defined total solid (TS), moisture on a free fat basis (MFFB), fat in dry solids basis (FDS) and salt to water ratio (SW).

45 min. Each vat is then predrained using a vacuum pump to remove 20% of the whey in the vats, and lifted to mould the curd in block-molds. Block-molds on draining mats and plates are stacked, inverted once and continuously transferred toward draining tables where the curd reaches a pH between 5.0 and 5.1. The next day, cheeses are unmoulded and placed on ripening racks. Stacks of 20 racks (to a total of 53 stacks per day) are deposited in a brining tank with a lifting hoist and are brined for 35 min. The saturated brine (26% w.w.⁻¹) maintained at 12 °C with a PHE is continuously filtered by a gravity filter (recirculation rate of 3 h⁻¹) and treated in-line by a UV light. Cheeses are subject to a *ressuyage* (yeasting) period of 24 h at 16 °C, 85% relative humidity, and are ripened for 11 d at 11 °C, 95% relative humidity. At the end of ripening, they are cooled at 4 °C for 24 h to avoid further formation of condensation in the package. Cheeses are finally packaged in an automated packaging machine, placed in boxes containing eight cheeses, palletized, and stored for 1 day at 4 °C prior to delivery. At unmolding, cheeses have a TS of 43%, but undergo weight losses of 3.5% during brining (Geurts et al., 1980) and 6.5% during ripening and storage

(Pointurier, 2003). It is assumed that 82%, 94% and 39% of the milk proteins, fat and non-fat solids (NFS), respectively, are retained in the cheese. Protein (and NFS, indirectly) recovery is higher than that suggested by Mietton and Chablain (2018), but is in accordance with the higher manufacturing yields expected with low concentration factor retentates (Banks, 2007). Cheese loss (i.e., cheeses with visual defects and underweights) represents 1% w.w.⁻¹ of the total cheese production.

2.3.2. Description of the MMV process

For the MMV approach, the process described by Mistry and Maubois (2004) was used, with the following modifications. Unlike the traditional process, the milk is not skimmed but it can be if the milk fat content is too high. Following the first heat treatment, the milk is cooled at 50 °C in the regenerative section of the pasteurizer and is ultrafiltered in a multistage UF system (5 stages) until reaching a MCF of 5.25. The two first stages are equipped with spiral-wound membranes (SWM), while the other three contain tubular (ceramic) elements because of the increasing

viscosity of the retentate throughout UF. A continuous diafiltration (DF, 0.33 diavolume) is performed in the last stage to reduce the lactose content of the retentate, thus lowering the post-acidification potential of the cheese. Following UF, a second heat treatment at 65 °C (15 s) is applied to the retentate for sanitary purposes. The energy of the retentate cooling to 40 °C is recovered to heat the DF water, while that of the UF permeate is used to preheat the raw milk in the first PHE. The permeate is cooled to 15 °C. For each maturation tank, the retentate is then inoculated with the same lyophilized cultures as for the traditional process, at 40 min intervals. It is enriched with sodium chloride (final concentration of 0.8% w.w.⁻¹) instead of calcium chloride. The higher maturation temperature (40 °C) compared to the traditional process is selected to reach the renneting pH of 5.2 as fast as possible (optimal growth temperature of the thermophilic acidifying culture). From this point, the retentate is renneted in-line and molded in unperforated block-molds. The block-molds are inverted once and the cheeses are unmoulded the next day. The ripening, packaging and storage conditions are identical to those of the traditional cheese. As confirmed by dairy processors, cheese loss is not significant in liquid pre-cheese processes but 1% of the retentate is lost because of its dilution during the water flush of the system at the end of UF.

2.3.3. Description of the From'Innov process

The From'Innov process is similar to the MMV process, with the following differences. Three days (72 h) prior to cheese production, four aromatic matrices are produced in bioreactors with different culture media: whole milk, cream (45% w.w.⁻¹ fat), concentrated whey (9% TS) made from whey protein powder (WPC35) reconstituted in water, and skim milk enriched with skim milk powder (15.8% TS). Fermentations with traditional cheese ripening microorganisms are performed at room temperature (21 °C). The matrices are added to retentate in the maturation tanks to a final concentration of 2% w.w.⁻¹ each (8% w.w.⁻¹ of aromatic matrices in the liquid pre-cheese). Since the matrices have lower TS than the retentate, they are concentrated at a higher MCF (5.64). The acidification of the liquid pre-cheese is enabled by the addition of δ -gluconolactone (GDL) at a concentration of 0.75% w.w.⁻¹ (Fetahagic et al., 2002). Following unmolding, a 24 h ressuage and 4 d ripening period allow the development of a mycelium on the rind of the cheese. No DF is required since post-acidification does not occur with such a short ripening time and with the use of GDL as acidifying agent. The retentate loss was the same as for the MMV process.

2.4. Cleaning procedures

The cleaning procedures are mostly performed by clean-in-place (CIP) systems. Operational parameters were selected following published recommendations (Bylund, 2003) and inspired by previous computer simulation models (Tomasula et al., 2013; Werne, 2016). Every processing surface (silos, pipes, tanks, pasteurizers, UF systems, etc.) is cleaned with an alkaline solution made of caustic soda (NaOH, 2% w.w.⁻¹). In addition, heated surfaces (pasteurizers) and UF systems are also cleaned with 1% w.w.⁻¹ nitric acid solutions. Each plant is equipped with distinct CIP systems for the milk pretreatment section (silos, pasteurizer, fat separator), the UF system, and the cheesemaking section (vats, molds, racks and mats, conveyors). As per industrial recommendations, the cleaning solutions are systematically fresh for the UF systems and are renewed by 10% prior to each use for the other sections. The water used to perform the first rinsing step is recycled from the water used to perform intermediate or final rinsing steps of the previous cleaning cycle (Walton, 2008). However, the water

used to perform the rinsing steps following alkaline and acid cleaning is always fresh.

The fluid velocity during cleaning is kept high enough to ensure a turbulent flow regime ($Re > 10^5$) (Walton, 2008). It is assumed that CIP of each section is carried out once per processing day (Tomasula et al., 2013) and that each CIP system is fed with water at 12 °C (Sun et al., 2011). A mean temperature loss of 3 °C is assumed during circulation of the solution through pipes and systems (Werne, 2016). It is also assumed that the cleaning solutions stored before reuse are kept at ambient temperature (22 °C).

Cheesemaking equipment (block-molds, draining mats and racks) are cleaned in an industrial tunnel-washer. The cleaning procedure includes a pre-rinse with reused water, cleaning with an alkaline solution and a final rinse step. Conveyors are cleaned with a foam cleaning machine. For more detailed information, all the assumptions made to perform the simulations are presented in Appendix D (Table D1).

3. Calculations

The predictive analysis of the three scenarios included the calculation of mass balances, and water and energy consumption. The results allowed the calculation of the economic balance of each scenario.

3.1. Mass balances

Mass balances were calculated from milk receiving to the end of ripening, assuming the final cheese composition specified previously (Mietton and Chablain, 2018). The chemical composition (Table 1), temperature and flow rate of the dairy inputs and outputs were obtained from a process prediction analysis in which all the unitary processes are connected. Milk loss was only considered following UF of the milk in the MMV and the From'Innov processes (1% w.w.⁻¹ of the final retentate mass) since the water flush of the UF system dilutes the liquid pre-cheese retentate, directly affecting the composition of the cheese. No value was allocated to this volume of UF retentate. Otherwise, milk losses were considered equivalent in the three processes, and were not calculated.

3.2. Water consumption

The consumption of water used to rinse the open surfaces (tanks, silos, conveyors) was 12.7 L m⁻².min⁻¹, as suggested by Tomasula et al. (2013). Since the other processing equipment (pipes, fat separator, PHE, UF system) is purposely filled with the CIP solutions and rinsing water at the cleaning stage, the required fluid volumes were assumed to be 120% of the dead volume of the equipment (Walton, 2008). However, since no data could validate this assumption, a sensibility analysis was performed on the number of dead volumes (DV) of water (1.2, 2, or 3) used to rinse them. The electricity, natural gas, and fresh water consumption were calculated for each number of dead volumes of water evaluated in the sensibility analysis.

3.3. Energy consumption

The mechanical (pumping, lifting) and cooling energies were from electrical sources and the heating energy was provided by the steam generated by a natural gas-fired boiler. All fluid-to-fluid heat transfers were performed by PHE. The equations used to calculate the energy consumption are reported in Appendix E. Data from the literature and from the industry were used to complete the information for some specific equipment, such as conveyors, vat lift, lifting-hoists, UV-lights or ripening rooms (Appendix D, Table D1).

Table 1
Composition of the dairy fluids involved during the production of 10,000 kg of soft cheese by three processes.

Process	Constituent	Inputs		Intermediate product	By-products			
		Raw milk	Aromatic matrix	Standardized milk	Cream	Whey ^a	UF permeate	DF permeate
Traditional	Mass (kg)	85,844		68,148	2,203	57,068	15,759	
	Protein (g.kg ⁻¹)	34.0		42.0	21.0	9.0	1.1	
	Fat (g.kg ⁻¹)	39.0		34.6	450.0	2.5	0	
	Lactose (g.kg ⁻¹)	44.0		44.2	25.6	50.2	45.7	
	TS (g.kg ⁻¹)	125.0		129.7	501.2	69.0	51.3	
MMV	Mass (kg)	56,299		10,611			45,580	3,573
	Protein (g.kg ⁻¹)	34.0		169.7			1.4	2.9
	Fat (g.kg ⁻¹)	39.0		202.4			0.0	0.0
	Lactose (g.kg ⁻¹)	44.0		33.0			44.0	33.0
	TS (g.kg ⁻¹)	125.0		427.2			49.8	38.7
From'Innov	Mass (kg)	52,702	805	10,720			43,350	
	Protein (g.kg ⁻¹)	34.0	36.5	173.3			1.4	
	Fat (g.kg ⁻¹)	39.0	145.6	213.9			0.0	
	Lactose (g.kg ⁻¹)	44.0	43.0	43.9			44.0	
	TS (g.kg ⁻¹)	125.0	234.8	454.2			49.9	

^a It was assumed that the whey was not diluted throughout the processing lines. The lactose content of the whey also included the minor proportion of lactic acid generated by starter cultures from lactose.

3.4. Physical constants

The physical constants of dairy fluids were mostly obtained from the literature. When available for specific temperatures, the specific gravity and the dynamic viscosity of the fluids were obtained from Walstra et al. (2006). Those of the milk retentates and the standardized milk were calculated from a regression model developed by Dinkov et al. (2008), while those for the cream were from Walstra et al. (2006) and Phipps (1969). The thermal conductivity of the fluids were obtained from Jeantet et al. (2011), while their specific heat capacities (kJ.kg⁻¹.K⁻¹) were calculated based on their moisture, protein, fat and ash contents (ASHRAE, 2006). The fluids were assumed to behave as Newtonian liquids.

3.5. Economic balances

The economic balance for each of the three processes was strictly dedicated to the production and ripening areas of the plants, according to the assumptions presented in Appendix D (Table D2). The incomes consisted of the selling price of the cheese and each by-product, namely defect cheeses, cream, whey and UF permeate. Indirect costs associated with the building, industrial processing equipment and human resources were considered in the expenditures. However, balances did not include costs associated with the other plant departments such as administration, quality control and assurance, wastewater management, etc. Human resources costs were estimated from the duration of the major processing steps in the three virtual plants. For manual operations such as unmolding or rack inverting during ripening, assumptions were made on an estimated working rate (i.e., 30 s to transfer cheeses from one block-mould to one ripening rack, or 1 min to invert one stack of 20 racks by two employees). It was also considered that two employees were needed to operate the tunnel-washer and packaging machines. Three managers (one per work shift) and two electro-mechanical technicians were also included in the simulations.

4. Results

The results are presented in three sections that cover mass balances, energy and natural resources consumption, and economic balances calculations.

4.1. Mass balances

Overall, the mass yields at unmolding of the liquid pre-cheese processes were greater for the MMV and From'Innov processes (19.00% and 19.39%, respectively) than for the traditional process (12.91%). Mass yields are defined as mass of cheese per mass of whole milk (and aromatic matrices for the From'Innov process) (Table 2). To make 10,000 kg of cheese, the traditional process needed 85,844 kg of whole milk, while the MMV and the From'Innov processes required 56,299 and 52,702 kg of whole milk, respectively (Table 2). The smallest amount of milk was used for the From'Innov process but 805 kg of aromatic matrices were added to the liquid pre-cheese prior to its coagulation (Table 1).

The traditional process generated larger amounts of by-products: cream (an excess of 2,203 kg not used for standardization), whey (57,068 kg) and UF permeate (15,759 kg), while only UF permeate and/or DF permeate were generated by the MMV and From'Innov processes (totals of 49,153 and 43,350 kg, respectively) since no draining step was performed in vats for these two processes (Tables 1 and 2). Non-fat solid recovery in the cheese was most efficient in the MMV and From'Innov processes, with 51.38% and 55.88%, respectively, compared to 39.31% for the traditional process (Table 2). These results are associated with the higher protein recovery of the liquid pre-cheese processes, because no cheese whey containing whey proteins was expelled from the curd, giving 95.22% for MMV and 95.71% for the From'Innov process, compared to 82.00% for the traditional process (Table 2).

At the same inoculation and renneting rates, the traditional process needed 6 times more rennet per kg of cheese produced than the other processes. Similarly, the need for cultures was higher during the traditional process, especially for acidifying cultures, since two inoculations were needed during the process (cold and warm maturations).

4.2. Energy and natural resources consumption

In the absolute, the traditional plant required less energy and natural resources. However, considering the high yields of the liquid pre-cheese processes, the From'Innov and MMV processes consumed less water (7.42 and 8.41 L of water per kg of cheese produced, respectively) than the traditional process (10.30 L of water per kg of cheese produced) (Table 3). Following the sensibility analysis, the From'Innov one remained the process that used the least fresh water per kg of cheese produced (Table 4).

Table 2
Mass balances of the production of 10,000 kg of soft cheese by three processes.

	Traditional process	MMV process	From'Innov process
Mass (kg)			
Inputs			
Raw whole milk	85,844	56,299	52,702
Whole milk (aromatic matrix)	–	–	201.27
UHT skim milk	–	–	166.96
Cream 45% w.w ⁻¹ of fat	–	–	241.52
Whey power (WPC35)	–	–	18.74
Skim milk powder	–	–	14.18
Calcium chloride 45% w.w ⁻¹	9.54	–	–
δ-Gluconolactone	–	–	76.18
Acidifying culture ^a	2.73 ^b	0.21	–
Ripening culture ^a	0.34	0.05	0.05
Rennet	15.47	2.43	2.31
Sodium chloride	78.55	80.23	79.58
Water ^b	–	3,573	162
Products			
Ripened cheese	10,000	10,000	10,000
Defect cheese	101	–	–
Cream 45% w.w ⁻¹ of fat	2,203	–	–
Cheese whey	57,068	–	–
UF permeate	15,759	45,580	43,350
DF permeate	–	3,573	–
Losses			
Retentate dilution ^c	–	107	94
Water evaporation ^c	1,080	695	221
Yields (% w.w⁻¹)			
Mass yield ^d at unmolding	12.91	19.00	19.39
Mass yield ^d after ripening	11.65	17.76	18.97
Protein recovery	82.00	95.22	95.71
Milk fat recovery	94.00	99.00	99.05
Non-fat solid recovery ^e	39.31	51.38	55.88

^a Cultures used in the simulations were lyophilized. The mass of acidifying culture of the traditional process includes both mesophilic and thermophilic cultures.

^b The water used in the MMV process was for the DF, whereas it was required to generate the aromatic matrices in the From'Innov process.

^c Losses consisted in the dilution of retentate during the water flush of the UF system, whereas the water evaporation was related to the loss of cheese moisture during ripening.

^d The mass yield includes the mass of the milk and the mass of the ingredients.

^e The non-fat solid recovery calculation includes the non-fat solids of the dairy ingredients.

Table 3
Fresh water and natural gas consumed (m³) during the production of 10,000 kg of soft cheese by three processes.

Natural resource	Processing step	Volume (m ³)		
		Traditional process	MMV process	From'Innov process
Fresh water	Production of aromatic matrices	–	–	0.16
	Fat separation (solids discharge)	0.25	–	–
	Diafiltration	–	3.57	–
	Cleaning-in-place	–	–	–
	Milk preparation section ^a	58.22	20.04	18.59
	Ultrafiltration system	5.67	42.17	37.35
	Cheesemaking section	27.64	12.59	12.73
	Steam generation	11.26	5.73	5.32
	Total per kg of cheese	10.30 x 10⁻³	8.41 x 10⁻³	7.42 x 10⁻³
Natural gas	Pasteurization #1	71.38	49.14	56.90
	Pasteurization #2	222.51	14.08	12.29
	Clean-in-place	352.79	265.82	236.53
	Total per kg of cheese	6.47 x 10⁻²	3.29 x 10⁻²	3.06 x 10⁻²

^a Milk preparation includes silos, tanks, pipes and pasteurizers.

A similar pattern was observed for natural gas consumption per kg of cheese produced. Again, the From'Innov process was the most efficient, consuming just 47.3% of the natural gas used in the traditional process (3.06×10^{-2} and 6.47×10^{-2} m³ per kg of cheese, respectively) (Table 3). The CIP systems accounted for the majority of the natural gas consumption for all three processes

because they use steam to heat the cleaning solutions. Differences between the cheese production processes were also observed during the second pasteurization, where, in the traditional process, a larger quantity of standardized milk had to be heated (68,148 kg vs 10,611 kg for MMV and 10,720 kg for From'Innov, Table 1), and from a lower temperature (12 °C vs 50 °C for MMV and

Table 4

Uncertainty assessment of the total natural resources and energy consumptions by varying the volume of water used to rinse filled equipment (from 1.2 to 3 dead volumes) during the CIP carried out in the three plants (mean values of the three scenarios \pm SD).

Variable predicted	Traditional process	MMV process	From'Innov process
Fresh water (L per kg of cheese)	11.15 \pm 0.66	9.07 \pm 0.68	7.94 \pm 0.54
Electricity (kWh per kg of cheese)	0.41 \pm 0.01	0.52 \pm 0.01	0.42 \pm 0.01
Natural gas (10^{-2} m ³ per kg of cheese)	6.81 \pm 0.22	3.47 \pm 0.19	3.20 \pm 0.15
Specific energy consumption (MJ per kg of cheese)	4.51 \pm 0.18	3.42 \pm 0.28	2.93 \pm 0.20

From'Innov).

The MMV process consumed the most electrical energy, with 0.51 kWh per kg of cheese, followed by the From'Innov and the traditional processes (0.41 and 0.40 kWh per kg of cheese, respectively) (Table 5). The DF was a demanding operation of the MMV process (Table 5). During the From'Innov process, the DF removal saved 795.87 kWh during the concentration step compared to the MMV process (Table 5), even if the milk had to be concentrated at a higher MCF (5.64 vs. 5.25) due to dilution of the milk through addition of aromatic matrices. The reduction of the ripening time of the From'Innov process saved 184.05 and 185.67 kWh per 10,000 kg of cheese compared to the MMV and the traditional processes, respectively, but it was not sufficient to reduce the total electrical energy use below that of the traditional process (Table 5).

Overall, considering electrical energy use and energy provided by the combustion of natural gas, the traditional process had the highest specific energy consumption (SEC) (4.32 MJ per kg of cheese produced). In comparison, SECs of 3.29 and 2.83 MJ per kg of cheese produced were obtained for the MMV and From'Innov processes, respectively (Table 6). The CIP processes were the most energy-demanding (Table 6), especially for the traditional process, in which 1.85 MJ per kg of cheese were used for CIP operations (1.45 and 1.28 MJ per kg of cheese for the MMV and From'Innov processes, respectively).

4.3. Economic balances

Briefly, for all three processes, the major expenditure was the milk, representing 72.0% of the total cost for the traditional process,

69.14% for the MMV process and 65.4% for the From'Innov process. Excluding milk, the highest daily expenditures for the traditional process were human resources (4.8%), the daily loan cost for industrial equipment (4.7%), cultures (3.6%) and natural resources (including electrical energy) (2.5%) (Table 7). The proportion of costs dedicated to electrical energy and natural resources was slightly higher for MMV and From'Innov processes, representing 3.3% and 2.8% of their expenditures, respectively (Table 7).

The three processes produced similar incomes (Table 7). However, the higher yields of the liquid pre-cheeses reduced expenditures, increasing the margin. In addition, the From'Innov process' use of dairy ingredients to produce aromatic matrices reduced the total cost of milk solids. Consequently, with cheese sold at 5.00 $\text{€}\cdot\text{kg}^{-1}$, it was the most profitable process (margin of 1.77 € per kg of cheese), followed by the MMV (1.75 € per kg of cheese) and the traditional process (0.96 € per kg of cheese) (Table 7).

5. Discussion

It is rather counter-intuitive to find that a liquid pre-cheese process could be less energy-demanding than a traditional process, as revealed by the calculation of SEC liquid pre-cheeses and traditional processes (Table 6). Indeed, a high level of mechanisation was assumed for the traditional cheesemaking process (automated processing line including mechanization of gel cutting, vat displacements along the conveyors, vat lifting for molding, mold inversion). However, although enhanced by low stirring, the draining step of the curd does not require external energy since it occurs naturally through coagulum syneresis (Dejmek and Walstra,

Table 5

Electrical energy consumption (kWh) of the unit processes involved in the production of 10,000 kg of soft cheese by three processes.

Processing step	Electric energy consumption (kWh)		
	Traditional process	MMV process	From'Innov process
Milk reception	7.57	4.97	4.65
Pasteurization #1	794.55	565.75	513.24
Skimming	129.12	–	–
Cream pumping and cooling	25.19	–	–
Production of aromatic matrices	–	–	2.00
Skim milk pumping to UF feed tank or standardization tank	23.27	1.12	1.04
Ultrafiltration	185.45	1,929.94	2,209.72
Diafiltration	–	1,075.65	–
UF permeate pumping and cooling	338.62	121.04	264.73
UF retentate pumping to standardization tank and cooling	12.52	–	–
Cold maturation	102.55	–	–
Pasteurization #2	328.78	81.90	109.43
Standardization and warm maturation	2.66	1.27	1.19
Cheesemaking	686.75	–	–
Whey pumping	1.45	–	–
Brinning	56.77	–	–
Ressuyage and ripening	312.05	310.43	126.38
Cheese cooling and packaging	20.23	19.73	20.54
Cold storage	111.55	95.61	89.50
Cold water pumping	5.34	0.20	1.10
Cleaning-in-place	776.97	759.39	644.75
Air compressor	111.11	111.11	111.11
Total per kg of cheese	0.40	0.51	0.41

Table 6
The specific energy consumption (SEC) of the most energy-demanding processing steps.

Processing step	Specific energy consumption (MJ.kg of cheese ⁻¹)		
	Traditional process	MMV process	From'Innov process
Pasteurization #1	0.60	0.42	0.44
Ultrafiltration	0.07	0.69	0.80
Diafiltration	0.00	0.39	0.00
UF permeate pumping and cooling	0.12	0.04	0.10
Pasteurization #2	1.11	0.09	0.09
Cheesemaking	0.25	–	–
Ripening	0.11	0.11	0.05
Cheese cooling and packaging	0.01	0.01	0.01
Cold storage	0.04	0.03	0.03
Cleaning-in-place	1.85	1.45	1.28
Compressed air	0.04	0.04	0.04
Others ^a	0.13	0.00	0.00
Total	4.32	3.29	2.83

^a Others gathers all the processing step consuming lower than 1% of the total energy.

Table 7
Economic balance for the production of 10,000 kg of soft cheese by three processes.

		Traditional process	MMV process	From'Innov process
Incomes				
Ripened cheese	5.00 €.kg ⁻¹	50,000	50,000	50,000
Defect cheeses	0.05 €.kg ⁻¹	5	0	0
Cream 45%	2.86 €.kg ⁻¹	6,295	–	–
Whey	0.02 €.kg ⁻¹	923	–	–
UF permeate	1.84 × 10 ⁻³ €.kg ⁻¹	29	90	80
Total (Incomes)	€	57,252	50,090	50,080
Expenditures^a				
Inputs				
Whole milk	0.40 €.kg ⁻¹	34,337	22,520	21,161
UHT milk	1.21 €.kg ⁻¹	–	–	201
Cream 45% w.w ⁻¹	2.86 €.kg ⁻¹	–	–	690
Whey powder (WPC35)	1.73 €.kg ⁻¹	–	–	32
Skim milk powder	1.76 €.kg ⁻¹	–	–	25
Calcium chloride 45% w.w ⁻¹	1.50 €.kg ⁻¹	14	–	–
δ-Gluconolactone	8.00 €.kg ⁻¹	–	–	609
Acidifying culture ^b	500 €.kg ⁻¹	1,363	107	–
Ripening culture ^b	1,000 €.kg ⁻¹	341	54	51
Rennet	1.60 €.kg ⁻¹	25	4	4
Salt	0.40 €.kg ⁻¹	31	32	32
Ripening paper	0.40 €.m ⁻¹	5,600	5,600	5,600
Natural resources and chemicals				
Electricity	11.50 × 10 ⁻² €.kWh ⁻¹	464	584	471
Fresh water	4.04 €.m ⁻³	363	296	261
Natural gas	57.13 × 10 ⁻² €.m ⁻³	369	188	175
Chemicals				
Caustic soda 35%	0.30 €.kg ⁻¹	41	128	103
Nitric acid 57%	1.16 €.kg ⁻¹	20	70	54
Chlorine 9.6%	3.77 €.kg ⁻¹	4	19	15
Foaming detergent	3.08 €.kg ⁻¹	7	6	6
Indirect costs				
Building	€.day ⁻¹	205	199	150
Industrial equipment	€.day ⁻¹	2,228	1,203	1,251
Human resources	€.day ⁻¹	2,288	1,539	1,504
Total (Expenditures)	€.day⁻¹	47,701	32,548	32,396
Margin	€.kg of cheese⁻¹	0.96	1.75	1.77

^a UK bulk cream price, liquid whey price in Italy, whole milk price in France including a transport fee, semi-skimmed UHT milk price in Italy, US value of whey protein concentrate price containing 34% of protein on a dry-basis, skim milk powder price in France were obtained from mean price value in 2017 (Italian Dairy Economic Consulting, 2018), UF permeate value was estimated from the permeate powder price (340 €.ton⁻¹) (Paterson, 2011), assuming transport and drying costs. Electricity and natural gas prices were the mean value of 2017, including taxes, for non-household consumers (Eurostat, 2018a, 2018b). Fresh water price was the mean value, including taxes, in France in January 2016 (Dequesne et al., 2018). Prices of other ingredients or inputs such as chemicals were obtained from European providers. References for indirect costs are detailed in Appendix D (Table D2).

^b Cultures used in the simulation were lyophilized.

2004), while high mechanical (pumping) energy must be transferred to the milk to perform the “draining” step (permeate removal by UF) during liquid pre-cheese processes. This result relates to the higher cheese yields of these processes, which were 52.4–62.8% higher than that of the traditional process after ripening (Table 2). As mentioned, the traditional cheese plant consumed fewer actual resources, but was less efficient since it consumed more energy and fresh water per kg of cheese produced (Tables 3 and 6) and generated a lower margin (Table 7).

The MMV process was found to be less efficient than the From’Innov process, mostly because of the DF, which required a larger active filtration area (31 m² of ceramic membranes) to acquire, operate and clean. In addition, the shorter ripening duration of the From’Innov cheese reduced both energy consumed per kg of cheese during the manufacturing process and indirect costs such as those associated with the plant’s land and buildings (lower surface area). This contributed directly to the increase in margin for the From’Innov process (Table 7).

5.1. The robustness of the predictive analysis

The SEC presented in this study for the traditional process (4.32 MJ per kg of cheese, Table 6) is similar to that of 4.3 MJ per kg of cheese reported by Ramirez et al. (2006). As in Berlin (2002), the traditional process consumed slightly more electrical energy per kg of cheese (1.5 compared to 1.3 MJ), but consumed less natural gas (2.9 MJ vs. 5.4 MJ). Both cheeses were uncooked, but the differences might simply come from the electrical energy required for the level of mechanisation of the plant, the natural gas composition or the efficiency of the boiler used to make the Swedish cheese. These details were not provided in Berlin (2002). Cheeses made in the Nordic countries, mostly hard and semi-hard cheeses, require between 0.41 and 2.84 MJ per kg of milk processed (Korsström and Lampi, 2001). As expected, values obtained through the simulation are in the lower part of the range (0.50–0.59 MJ per kg of milk processed for all cheeses simulated, data not shown). Indeed, the SECs of soft cheeses are lower than the average because their processes do not include a cooking step (Ramirez et al., 2006). The SECs of liquid pre-cheese processes were lower per kg of cheese (Table 6), along with their high production yields (Table 2).

Even though few studies have carried out energy consumption assessments in cheesemaking plants, it was still possible to compare the data with other kinds of dairy plants, such as fluid milk plants in which common processes are performed, notably pasteurization or CIP. For example, Natural Resources Canada (2001), using a raw milk density of 1035.9 kg m⁻³ (Walstra et al., 2006), measured an SEC between 0.07 and 0.75 MJ per kg of milk in 17 Canadian plants for the homogenization and the pasteurization processes measured together. In the USA, Tomasula et al. (2013) calculated a value of 0.04 MJ per kg of milk for the pasteurization process alone. The values predicted in this study for the first pasteurization (Table 6), between 0.42 and 0.60 MJ per kg of cheese (corresponding to between 0.07 and 0.08 MJ per kg of milk processed, data not shown), appeared realistic since the regeneration efficiency of the pasteurizer is more effective in fluid milk plants due to the lower outlet temperature of the milk (Tomasula et al., 2013).

Large variations in CIP were also reported among Canadian plants, ranging between 3.48×10^{-4} and 0.32 MJ per kg of milk, or a mean value of 0.15 MJ per kg of milk (Natural Resources Canada, 2001). A value of 0.11 MJ per kg of milk was obtained by Tomasula et al. (2013). Since more equipment was included in this study (i.e., filtration system, automated processing lines, conveyors and cheesemaking equipment), more water or cleaning solutions required heating. This could explain the high (although still in the

range) energy demand calculated to carry out the CIP operations in the virtual plants. These results were between 1.28 and 1.85 MJ per kg of cheese (Table 6), which corresponded to values between 0.21 and 0.26 MJ per kg of milk processed (data not shown).

The most difficult parameter to predict remained the fresh water consumption because only general data is available in the literature, and studies measuring it in cheesemaking plants did not provide details about the types of equipment used (types of vat, molds or washers, the level of automation, the use or not of UF). Saraiva et al. (2009) measured a value of 1.55 L of water per kg of milk processed during the production of mozzarella in a small-scale dairy plant (4000 L of milk processed per day), while values between 1.59 and 18.77 L per kg of milk processed (mean value of 3.09 L per kg of milk) were measured in Portuguese cheesemaking plants (Costa, 2011). The cheesemaking process requires between 1.60 and 3.66 L per kg of milk processed in Nordic dairies, or between 0.6 and 1.2 L per kg of milk for the production of a soft cheese in France (between 0.6 and 5.5 L per kg of milk for cheesemaking plants around the world) (International Dairy Federation, 1981). Except for the values of the IDF, the fresh water consumptions of 7.42–10.52 L per kg of cheese (corresponding to 1.20–1.49 L per kg of milk processed) estimated in this study were lower than expected, even for the worst-case scenario of the sensibility analysis (Tables 3 and 4). It is assumed that the prediction method used might have led to uncertainty, and that further work at the pilot scale is needed to determine precisely the consumption of water for all scenarios presented. It will be of interest to measure all the water losses or the water needed to clean the floors of the plant. However, since the sensibility analysis confirmed that even if the predictions were deliberately increased with higher volumes to rinse the filled equipment (up to 3 dead volumes), the uncertainty related to the values predicted remained low. It is also important to mention that for each scenario of the sensibility analysis, the From’Innov process consumed less water and energy than the traditional or the MMV processes (Table 4).

5.2. Limitations of this study and further improvements of the From’Innov process

The predictive analysis described here was carried out only for the production of a Camembert-type soft cheese. In countries where GDL is not allowed in cheesemaking, the From’Innov process would need a DF to avoid a ripening defect affecting the cheese texture due to cheese post-acidification. For the production of a soft cheese, the DF would negate the economic and environmental advantages, compared to the traditional process. Indeed, with a difference of only 7 days between the ripening durations of the From’Innov and traditional processes, the benefits of reducing the ripening time are limited. However, the environmental gain associated with the From’Innov process could potentially be higher for semi-hard cheeses (e.g., St-Paulin, which can be made by the MMV process [Goudéranche et al., 1980]) which are traditionally ripened for longer durations (weeks to months). The semi-hard cheeses would, however, require further concentration of the milk, thus affecting the production yield, the membrane surface area and the energy consumed to reach the required TS content. Further studies are needed to investigate the potential benefits to other kinds of cheeses.

Moreover, it was assumed that the three processes generated cheeses with similar organoleptic properties, which is rather unlikely, even with equivalent chemical compositions. Indeed, no whey is expelled from the curd during the liquid pre-cheese processes (i.e., MMV and From’Innov cheeses), resulting in cheeses with higher concentrations of whey proteins and calcium, which have major effects on cheese texture (Maubois and Mocquot, 1975).

If these proteins soften the cheese texture by increasing the water content (Hinrichs, 2001), they can also retard cheese ripening, depending on their denaturation rate (Guinee et al., 1995). The increased level of calcium can also lead to crumbly or sandy textures (Brulé et al., 1975), but these textural properties can be controlled by optimizing the operational parameters during UF (Brulé et al., 1975), or the retentate composition or the properties prior to renneting (Karlsson et al., 2007). It is known that increasing the coagulation temperature can form stronger hydrophobic bonds in the cheese matrix, which could strengthen the cheese texture (Wium et al., 2003). This opportunity could potentially allow a reduction in the TS content of the cheese and increase the mass yield for a texture equivalent to that of the traditional cheese. Consequently, further studies that include texture elements or more accurate composition ratios, including calcium or whey protein content in the functional unit, may improve the quality of the comparison between traditional and liquid pre-cheese processes.

6. Conclusion

The From'Innov process could be at the root of a profound change in cheese technology, notably by replacing traditional cheese ripening in cold rooms with incorporation of aromatic matrices in a liquid pre-cheese prior to its coagulation. This preliminary work provided interesting insights on the potential of the From'Innov process to reduce the energy and fresh water consumption of the cheesemaking process. Indeed, based on data generated from a predictive model or obtained from industry, this study also confirmed that the From'Innov process is economically viable. Its profitability could even be increased after characterization of From'Innov cheese texture, which is affected by several key production parameters such as pH, temperature and TS content of the liquid pre-cheese. Further investigations related to carbon and water cycles of the whole process will allow to determine how From'Innov could reduce the environmental impact of cheese.

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Appendix A. Supplementary data

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