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Almena Ruiz, Alberto; Fryer, Peter; Bakalis, Serafim; Lopez-Quiroga, Estefania

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Alberto Almena
Email: axa1122@student.bham.ac.uk
School of Chemical Engineering
University of Birmingham
Birmingham B15 2TT, UK

Peter J. Fryer
Email: p.j.fryer@bham.ac.uk
School of Chemical Engineering
University of Birmingham
Birmingham B15 2TT, UK

Serafim Bakalis
Email: serafim.bakalis@nottingham.ac.uk
Faculty of Engineering
University of Nottingham
Nottingham NG7 2RD, UK

Estefania Lopez-Quiroga*
*Corresponding author
Email: e.lopez-quiroga@bham.ac.uk
Phone: +44(0) 121 4145080
School of Chemical Engineering
University of Birmingham
Birmingham B15 2TT, UK

Local and decentralized scenarios for ice-cream manufacture: a model-based assessment at different production scales

A. Almena[a] , P. J. Fryer[a] , S. Bakalis[a,b], E. Lopez-Quiroga[a*]
[a]School of Chemical Engineering, University of Birmingham, B15 2TT, UK
[b]*Faculty of Engineering,* The University of Nottingham, NG7 2RD, UK

Abstract

Decentralised food manufacture – e.g. a cloud of small local production sites and shorter distribution networks – can be a powerful tool in the development of more sustainable and safe food chains. In this context, new processing scenarios based on emerging "on-demand" and "sharing" models, together with distributed manufacture methods, are potential alternatives to the current centralised paradigm. However, studies on how these new processing scenarios might unfold are scarce.

This work presents a techno-economic and carbon footprint assessment of different ice-cream manufacture scenarios, i.e. Multi-Plant (MP), Single-plant (SP), Distributed Manufacturing (DM), Food Incubator (FI) and Home Manufacturing (HM) that cover a wide range of scales (0.01 kg/h to 50,000 kg/h) and increasing decentralised production. Results revealed at what production level different processing scales become profitable, demonstrating that the shift on manufacture paradigm can be studied as a scale-down engineering problem and showing how decisions between local and centralised manufacture can be made.

Keywords: decentralised food manufacture; ice cream; modelling; energy use; profit; carbon footprint.

Nomenclature

Lowercase

a	width dimension (m)	m	mass (kg)
b	length dimension (m)	$\dot{m}$	mass flow (kg s^{-1})
c	flow window or open section (dimensionless)	*n*	flow behaviour exponent (dimensionless)
c_p	heat capacity (kJ kg^{-1} ˚C^{-1})	p	price ($)
d_h	hydraulic diameter (m)	q	annual production (kg year^{-1})
e	spacing (m)	r	radius (m)
f	fouling factor (W m^{-2} K)	t	time (s)
f_{shape}	shape factor	v	linear velocity (m s^{-1})
g	gravitational acceleration (m s^{-2})	x	mass fraction
h	individual heat transfer coefficient (W m^{-2} K^{-1})	x'	mass fraction solute/solvent
k_{sv}	solvent factor (˚C g mol^{-1})	Δp	Pressure loss (Pa)
l	length (m)		

Uppercase

A	surface (m^2)	$\dot{M}$	production rate (kg h^{-1})
C	circumference (m)	N_P	Power number
COP	coefficient of performance for a refrigerant	Nu	Nusselt number
D	diameter (m)	OC	Operation Cost ($ year^{-1})
F	experimental factor (dimensionless)	Ov	overrun percentage
FPF	freezing point factor	P	Power/Shaft work (W)
GWP	global warming potential (kgCO$_2$e kg^{-1})	Pr	Prandtl number
G	mass flow per surface unit (kg m^{-2} s^{-1})	Q	heat (J)
$HTST$	High temperature short time	$\dot{Q}$	heat flow (J s^{-1})
IPS	Iron pipe size (in)	Re	Reynolds number
K	consistency index (Pa.s^n)	SE	equivalent of sucrose (kg mol^{-1})
L	latent heat (kJ kg^{-1})	T	temperature (˚C)
LHV	low heating value (kJ m^{-3})	TS	total solids content (%)
$LTLT$	low temperature low time	U	global heat transfer coefficient (W m^{-2} K)
M	molar mass (g mol^{-1})	V	volume (m^3)
N	number of	$\dot{V}$	volume flow (m^3 s^{-1})

Subscripts

0	starting point	*lb*	lower bound
app	apparent	*lm*	logarithmic mean
b	freezing barrel	*mix*	pre-frozen mix
b-d	batches in a daily base	*msnf*	milk solids non fat
bf	baffle	o	outer
c	cylinder	*out*	outlet
cond	condensate/condenser	p	plate
cont	continuous phase	*p-d*	actual productive time in a daily base
corp	corporation	*past*	pasteurisation
e	external	PHE	plate heat exchanger

$evap$	evaporator	pt	port
f	fusion	raw	pre-pasteurised mix
fd	freezing point depression	ref	refrigerant
hom	homogenised	reg	regeneration
i	inner	ss	stainless steel
ic	ice cream	st	solute
ice	ice phase	sv	solvent
ii, jj	iteration step	t	turbine
IF	initial freezing	u	useful
im	impeller	ub	upper bound
in	inlet	v	vessel
j	individual food component	VAT	value added tax
jk	jacket	w	water
k	dissolved substance	$wall$	property by the wall
Greek Symbols			
$\dot{\gamma}$	shear rate (s^{-1})	μ	viscosity (Pa s)
Γ_h	horizontal tube loading (kg m^{-1} s^{-1})	Π_{fac}	net profit per facility (\$ $facility^{-1}$ $year^{-1}$)
δ	thickness (m)	ρ	density (kg m^{-3})
ε	volume fraction	τ	tax percentage (%)
η	yield	χ	conservation property
λ	thermal conductivity (W m^{-1} k^{-1})	ω	rotational speed (s^{-1})

1. Introduction

Sustainability has become a critical factor in the design of food manufacture systems (Govindan, 2018; Rohmer et al., 2019), as the need to mitigate the environmental impacts of food processing - one of the major responsible of fossil fuels consumption and GHG emissions (FAO 2017; Department for Business, Energy and Industrial Strategy , 2018 & 2019; EIA 2019; Ladha-Sabur et al., 2019) - grows more and more urgent (IPCC 2018). The current challenge lies in implementing manufacture processes that involve lower environmental damage and generate positive social impacts (e.g. higher engagement between local producers and consumers), while keeping economic competitiveness (Akbar and Irohara, 2018).

In this context, alternative production scenarios based on emerging “on-demand” and “sharing” models, together with distributed manufacture methods (Almena et al., 2019), are potential alternatives to increase sustainability across the food supply chain. Such alternative methods are based on a restructuring of production into decentralised small-scale facilities (Sellitto et al., 2018; Jarosz, 2018; Angeles-Martinez et al., 2018), which shortens distances to consumers – thus decreasing energy use and emissions linked to product transportation and storage (Srai et al., 2016) – and/or involves more sustainable and ethical practices into the manufacturing processes (Cottee, 2014; Rauch et al., 2017). All these changes are facilitated by (i) the increasing digitalisation of the food sector, which minimises logistics cost (Kagermann, 2015; Maslarić et al., 2016) (ii) the growth of ICT (i.e. Information and Communications Technologies), which speeds up interaction between manufacturers and consumers (Miranda et al., 2019), and (iii) new manufacturing technologies, such as additive (Freeman and McMahon, 2019) and modular manufacturing (Baldea et al., 2017), which concept might be better suited for decentralised structures.

Within this frame of reference, this works presents a model-based techno-economic and environmental (i.e. carbon footprint) assessment to show how those alternative decentralised scenarios might compare to centralised ones at different processing scales. This work does not consider transportation costs or attempt formal optimisation of the process and/or scheduling. The aim here is to identify and compare the ranges of conditions at which the different processing scales might be sustainable (both in economic and environmental terms). We have used ice cream as food exemplar since, in ice cream manufacture, low volume and local business (i.e. ice-cream vans and parlours) already coexist with industrial processing, providing a realistic framework for the study. Ice cream also combines consumer popularity, complexity as a food system (i.e. it is a frozen and structured multiphase product) and a highly energy-intensive manufacture stage – 11%-14% of the total, considering a cradle to grave approach (Konstantas et al., 2019b).

Current literature focuses mainly on modelling and/or optimisation of single stages of ice cream manufacture, such as freezing/crystallisation (Cogné et al., 2003b; Arellano et al., 2013b,2013c; Bayareh et al., 2017; Hernadez-Parra et al., 2018) or storage (Tsevdou et al., 2015). There are a few works modelling properties that depend on product formulation such as viscoelasticity (Rahman et al., 2019) or thermal properties (Cogné et al., 2003a), while environmental impact assessments of ice cream offer only lumped results for the manufacture step (Konstantas et al., 2019a and 2019b). To the best of our knowledge, the literature does not contain models for all the stages in ice cream processing, together with profitability and environmental (i.e. carbon footprint) evaluation.

To fill this gap, we have used a modelling tool (Almena et al., 2019) to (i) define artisan and industrial processing methods (i.e. unit operations involved, as well as corresponding energy and material balances) (ii) estimate production costs (iii) evaluate environmental impacts as carbon footprint for a wide range of ice cream processing scales. Different levels of complexity (e.g. product microstructure and multiphase nature, number of unit operations or production lines) and uncertainty sources (e.g. fluctuation of raw materials and/or energy prices) were considered in the model. The methodological framework has previously been used to study a dry-mix product (Almena et al., 2019); here we extend for complex foods, i.e. ice-cream. The novelty of this approach is two-fold:

(i) It presents a *virtual* ice cream processing facility (both at plant and home-made scales). This connects energy and mass flows as per characteristic processing flowsheets and uses ad-hoc designs for each unit operation – i.e. industrial equipment is selected and sized according to production rates, operating conditions and product formulation to satisfy energy and material balances of each processing step.

(ii) It provides a scenario-based, flexible and robust tool that supports decision-making and strategic planning for ice cream processing at all production scales. This tool present potential for helping food manufacturers and stakeholders to assess economic and environmental performance (i.e. carbon footprint) of their processes, step by step, setting the basis for more sustainable food processing methods.

2. Materials and Methods

2.1. Ice cream formulation

Two different ice cream mixes (i) standard and (ii) premium were investigated. The main components in both formulations were: fats (milk and non-milk), milk solids-non-fat, sweeteners, emulsifiers, stabilisers and water. The product compositions can be found in Table 1. The overrun for the standard ice cream was 100-120%, while for the premium ice cream it was 25-50 %. In addition, for standard ice cream, two flavours (vanilla and chocolate) were considered.

2.2 Manufacture methods

Two different paradigms for ice-cream manufacture have been analysed: industrial and artisanal production. This classification follows the methodology presented in Almena et al. (2019), where food manufacturing methods where characterised in terms of (i) the degree of decentralisation and (ii) the production scale (i.e. throughput).

2.2.1 Industrial manufacture

Industrially, ice cream manufacture takes place in single (SP) or multiple (MP) industrial plants. This scenario represents high-volume production and the most centralised manufacturing model.

Figure 1 shows a designed flowsheet for both standard and premium ice cream process lines. Pasteurisation is performed in batch for production rates below 600 l/h (Goff and Hartel, 2013), while for larger throughputs, the process uses continuous operation. Table 2 lists the main operating conditions of the process, together with equipment selected to perform the corresponding unit operations.

2.2.1 Artisanal manufacture

Artisan methods make use of the same unit operations than industrial methods but use equipment suitable for low or very low throughputs (e.g. home-made scales) and batch operation. This manufacture method covers three different production scales:

i) *Home Manufacturing* (HM), based on domestic kitchen production (i.e. the smallest throughput per facility). This is the most decentralised manufacture method, with freelance workers following the 'gig-economy' model and selling home-made ice cream on-demand (Gleim et al., 2019).

ii) *Food incubator* (FI), where under-utilised assets, such as specialised equipment and facilities, are rented by freelance workers to produce ice cream in an on-demand basis (Alonso-Almeida et al., 2020).

iii) *Distributed Manufacturing* (DM), which represents a modular manufacturing approach, with small catering size facilities scattered within a region/country. This scale assumes a combination of sole proprietorship and corporation model with two management cost alternatives: *low management* (*franchise)* and *high management (company)*.

Table 3 lists the equipment used by the three artisanal methods. HM and FI scales follow the flowchart shown in Figure 2(b), which is based on the use of common kitchenware.

2.3 Modelling approach

A two-layer model has been used for process design, techno-economic and environmental assessment (i.e. carbon footprint) of ice cream manufacture scenarios:

- The *lower layer* of the model consists of a set of mass and energy balances used to design the process unit operations as defined by the corresponding flowsheets (industrial or artisanal) – i.e. a virtual process for ice cream manufacture. This layer is also responsible of characterising the different ice-cream formulations considered (e.g. thermal properties, viscosity). Outcomes are used to estimate energy demand per process/scale across a wide range of throughputs.
- The *upper layer* is responsible for the environmental and economic analysis, assessing the viability of each production scenario according to estimated profits and carbon footprint impacts.

The model can also consider different levels of complexity (e.g. number of unit operations or production lines) and uncertainty sources (e.g. fluctuation of raw materials and/or energy prices). It was implemented and solved in Matlab, with unit operations defined as subroutines and a main programme calling the sequence of events as per flowsheet. All the assumptions made for each manufacture scale are provided in the Supplementary Material.

2.3.1 Modelling assumptions

A number of assumptions have been made to define the operation of the different manufacture methods and production scales (e.g. equipment specs, labour conditions, etc). A complete list is provided in the Supplementary Material. Due to space restrictions, only some of the general ones are presented here.

- This work does not include production of raw materials, distribution nor retail. It only focuses on the processing stage.

- Standard ice cream is sold in one litre cups, while two formats –150 ml and 500ml– are considered for premium ice cream. Average market prices were taken from the four biggest UK supermarkets - 3.5 £/unit, 3 £/unit and 5 £/unit respectively (Tesco, 2019; Sainsburys, 2019; Asda, 2019; Morrisons, 2019).- and converted into USD$ (i.e. 4.52 $/unit, 3.87 $/unit and 6.47 $/unit, respectively).
- There are no product changeovers assumed.
- Ice cream overrun for the standard ice cream is 110% and for the premium ice cream is 27%, following the cited commercial product examples.
- A waste factor of 0.1 % and 0.5 % per unit operation for the industrial and artisan processes is, respectively, accounted in the mass balances.
- Value added tax for ice cream in the UK is 20% of its market price (Government of United Kingdom, 2019a) and the Corporation tax reduction is the 19% of the Gross Profit (Government of United Kingdom, 2019b)
- Management cost was estimated following the procedure detailed in Almena et al. (2019).
- An operation mode of 5 days and 2 shifts (Maroulis and Saravacos, 2008) is assumed for the ice cream plant, allowing overnight ageing of the mix. The plant annually closes for 4 weeks to perform maintenance.
- The operation mode for HM and FI is 5 days and 1 shift, as they represent a freelance worker scenario. DM replicates industrial processing, operating 5 days and 2 shifts.
- For artisan scales, cleaning time of 1 h is assumed within the daily working time; for industrial production, a daily starting up time of 15 min and a cleaning time of the line of 2h were considered (Kopanos et al., 2012).
- Only one production line is assumed per facility, either artisan or industrial. For artisan scales, HM uses one piece of each equipment, FI has two items of each instrument available, and DM processing line consists of a single module per unit operation.

- Working capital is assumed to be the production cost of one month of ice cream, meeting the product storage time of common ice cream industrial plants (Goff and Hartel, 2013). Same assumption was made for the artisan scales.

2.3.2 Ice cream thermophysical properties and rheology

Thermophysical properties (specific heat, density, thermal conductivity) are defined using mixing rules based on the recipe for the different formulations (see Table 4 for a complete description). For each one of the main constituents (water, protein, fat, carbohydrate, fibre and ash) those properties are defined as temperature dependent functions using formulae from Choi and Okos (1986) formulae (Table A.1 in Supplementary Material). Equations used to define the ice-cream freezing point depression, ice fraction and overrun are also given in Table 4. The expressions used to characterise the viscosity of the ice-cream along the different stages of the manufacturing process (pre-frozen and frozen mixes) and through the different pieces of equipment are listed in Table 5.

2.3.3. *Process modelling*

For each unit operation (e.g. freezing, pasteurisation) included in the process flowsheets, mass balances are used to (i) calculate the raw materials needed (ii) size the equipment required for a given production rate. Likewise, energy balances and thermodynamics are used to design the processing equipment to compute the energy requirements of the different processes. No accumulation is assumed in any of the process units.

To calculate daily production at artisan scales, the processing time of a batch (t_{batch}) is computed for each piece of equipment as follows (see Nomenclature for terms definition):

$$t_{batch} = 3600 \times \left(N_{batch-hour}{}^{unit}\right)^{-1} = 3600 \left[\frac{N_{unit}\dot{M}_{unit}}{F_V\, V_{unit}\, \rho_{ic}}\right]^{-1} \qquad \text{Eq. 16}$$

The maximum number of batches and volume of mix that can be produced at each stage during a workday are then estimated considering the time window available for non-overlapping processes. A material waste factor of 0.5% accounts for losses after each batch. The upper limit for each of the artisan scales (HM, FI and DM) is given by the maximum quantity of product that can be produced in a day. The resulting daily production of a single facility is then used to estimate the annual production.

For industrial methods (SP and MP), the model selects the most suitable equipment size (as given by commercial catalogues) depending on the given throughputs for the continuous process lines. This requires specific sub-routines for the design of the following industrial equipment: (i) stirred jacketed vessel (ii) plate heat exchanger and (iii) surface scraped heat exchanger. A more detailed description of this design step as well as a schematic representing the decision-making algorithm for each piece of equipment in given in the Supplementary Material (Tables A.3-A.5).

Finally, for both industrial and artisan methods, the ratio between the theoretical energy transfer resulting from the energy balances and the equipment input power given by the manufacturer will allow to compute the efficiency of each unit.

2.3.4. End-use energy demand and carbon footprint evaluation

For artisan manufacture (HM, FI and DM), the process is fully electric and the energy use per batch is calculated from the sum of the power consumption of each piece of equipment (as per technical specifications). At industrial scales (SP and MP), processing equipment (including pumps and cooling/freezing devices) uses electricity, while auxiliary water heating (e.g. for pasteurisation) used a boiler fuelled by natural gas. Experimental correlations used to calculate electric power requirements as well as the expression used to calculate the energy supply to the boiler can be found in the Supplementary Material. The carbon footprint of the process given as GHG emissions was computed using energy demand by source and conversion factors in Government of United Kingdom (2019c).

2.3.5. Economic evaluation

Cost has been estimated following the methodology presented in Almena et.al. (2019), which includes uncertainty in both operating and capital costs. The operating cost comprises variable (e.g. raw materials, utilities, packages) and fixed components (e.g. depreciation of instrumentation, rent fees, labour, maintenance). The total capital represents the initial investment necessary to build the facility and start-up the process–e.g. industrial machinery cost (correlations given in Table A.9, Supplementary Material). Tables A.11 and A.12, also in the Supplementary Material, list the individual factors used for costing each manufacturing scale. Profitability of each scenario was calculated using the following expression for the net profit (see Nomenclature for terms definition):

$$\Pi_{fac} = \left(1 - \frac{\tau_{corp}}{100}\right)\left[\left(1 - \frac{\tau_{VAT-ic}}{100}\right)(q_{ic}\, p_{ic} - OC_{ic})\right] \times \left(\frac{1}{N_{facilities}}\right) \qquad \text{Eq.17}$$

It is assumed that all units produced are sold and the sales revenue is equally divided among all the facilities. A sufficient/positive annual net profit guarantees economic benefits for a given manufacture scenario.

3. Results and Discussion

3.1 Unit cost at multiple manufacturing scales

A comparison of unit costs per kilogram of product for the five manufacturing models –HM, FI, DM, SP and MP– is presented in Figure 3(a). All the manufacturing scenarios were modelled across a production rate ranging from 0.01 kg/h to 50,000 kg/h, with maximum capacities per facility of 3.0 kg/h for HM, 8.7 kg/h for FI and 21.8 kg/h for DM. Premium ice cream, sold in packages of 500 ml at a market price of 12.4 $/kg, was chosen as the reference product for this comparison. For all methods, the cost curves can be divided in three regions:

- *Unfeasible region*, characterised by the steepest slope - slightly smaller capacities significantly increase the unit cost.
- *Plateau region*, defined by throughputs for which additional increases will not cause any further cost effectiveness – i.e. no changes for unit costs.
- *Transition region*, located in between the other two - production within this region will take full advantage of economies of scale, with significant cost reductions for slightly larger capacities.

Results reveal that for artisan scales, HM generates larger profits (unit cost below market price) operating at throughputs of 1 kg/h, while DM with low management is cheaper than both HM and FI unit costs at intermediate production rates (100-1000 kg/h). At industrial scales, a single plant with a capacity below 650 kg/h will not be profitable, while larger plants above 3325 kg/h – i.e. in the plateau region – will see no profit gains for operating at increasing production rates. Feasible throughputs shift to production rates between 950 kg/h to 4550 kg/h for a two-plant scenario.

Producing smaller packs of ice cream results in higher unit costs for all scales, as can be seen by comparing unit costs for 500 ml packages in Figure 3(a) to cost data presented in Figure 3(b) for 150 ml packages. For example, production costs rise 50% and packaging cost increases by 6 times for industrial scales producing the smaller format, while for artisan-based scales, the unit cost for both HM and FI scales increases above DM costs because of higher management fees for the latter, which have been calculated as a multiplier of sales revenue following the ‘gig economy’ model.

Figure 3(c) shows unit cost changes with throughput for standard ice cream sold in 150ml packages. In this case, centralised manufacturing reduces the production cost by 50% in comparison to the premium variety shown in Figure 3 (b), as the standard formulation uses cheaper raw materials (see Table A.10 in the Supplementary Material for prices) and has a greater overrun. Artisan scales require much larger number of facilities than industrial methods to produce the same mass output, due to both the lower density of the standard ice cream and the invariant volume capacity of the instrumentation. DM costs are similar to premium ice cream manufacturing and cannot compete with HM and FI.

3.2 Influence of the manufacturing scale on the total capital and labour

Artisan manufacturing scales, such as HM and DM, show a linear increase in capital with production rate. The lowest investments are required for FI scales, as it is assumed that the assets are rented by the freelance workers, so that only working capital is needed to start the business. HM is assumed to use only pre-owned and common equipment, so this scale does not require initial capital but must account for equipment depreciation and replacement as cost. At the DM scale, the amount of management does not influence total capital, i.e. there are no differences between low and high management scenarios. Modular production lines are cheaper than high-volume plants at production rates below 5000 kg/h but become more expensive at higher throughput. For example, for a production of 3700 kg/h, 158 DM facilities require a similar investment than a single industrial plant with the same output. Industrial scales show a stepped progression resulting from the integration of additional equipment when maximum capacities are reached. If the production is divided in two operating plants, the total capital follows a parallel trend to SP, with an averaged addition of $8 million.

Personnel and organisational charts for each manufacture scale are provided in the Supplementary Material (Figs. A.4 and A.5). According to those descriptions, SP scenarios result in the lowest manpower among the industrial scales, independent of the capacity of the production line. This is in contrast to the manpower needed for artisanal manufacturing scenarios, which is inversely proportional to facility size. For DM facilities, production per worker increases as specialised equipment is used, so fewer workers are needed. The required manpower can be considered as social impact indicator for each scenario (Hale et al., 2019; Dufour, 2019).

3.3 Energy consumption of industrial and artisan manufacturing processes.

Figure 4(a) shows specific energy use (in kJ/kg product) as a function of the production rate for premium ice cream processing in an industrial plant. Total value as well as individual contributions from heating, refrigeration and electric processes are shown. The discontinuity shown for the refrigeration and heating curves – pointed out with an arrow in Figure 4(a) – is due to the change from batch to continuous pasteurisation (continuous operation saves heating and cooling energy by including heat regeneration). Energy use for a single plant, sourced by a combination of electricity and natural gas, reaches a minimum at *ca.* 1300 kg/h production rates. Higher ice cream production on a single line leads to higher head loss, at the plate heat exchanger (PHE), so pumping power - and overall energy demand - rises above throughputs of 3250 kg/h. This energy use minimum shifts towards higher throughputs as the number of production lines and/or plants increases.

Artisan-based manufacturing scales, which are fully electric powered, show a constant value of specific energy consumption for production capacities above 100 kg/h, as shown in Figure 4(b). At lower volumes, discontinuities are seen due to the addition of new facilities with non-full storage units. HM proves to be the most energy effective of the artisanal scales (1150 kJ/kg), followed by FI that uses 10% more. DM requires 1780 kJ of electricity per kg of ice cream produced, thus increasing the energy demand of the artisan process by 55%.

Energy consumption for ice cream production has been reported within 1.90 and 3.70 MJ/kg (Ladha-Sabur et al., 2019). If only ice cream manufacture is considered – assuming that the raw materials are bought ready-to-use and they do not require any transformation that adds up to energy demand – the overall energy consumption decreases to 0.70 MJ/kg (Foster et al., 2006; Fisher et al., 2013). This indicates that significant energy demand reductions are achievable by the industrial scales operating with more than one production line/plant, since the energy use minimum (*ca.* 0.6 MJ/kg) shifts towards the region of profitable production rates (>10^4 kg/h, as in Figure 3) when the number of lines/plants increases. On the other hand, the three artisan scales can duplicate (HM and FI) or even triplicate (DM) industrial energy demands when operating at profitable production rates (1-100 kg/h, as in Figure 3).

3.4 Case study: UK ice-cream demand scenario.

This section presents an analysis of possible different manufacture scales for an ice-cream production scenario based on UK annual demand, which was approx. 328M litres in 2018 (ONS, 2019). According to this, a production rate of 86,500 kg/h (considering the industrial operation mode) is needed to satisfy the UK demand. Assuming that the demand is satisfied by selling only premium ice cream in packages of 500 ml, the UK supplied by a HM model would comprise 49,744 scattered facilities over the country, employing an equivalent number of individuals. FI would reduce this number to 19,630 facilities, due to an increase in the production per facility and worker.

For DM, the catering sized scale would involve 3,676 local branches to reach the required ice cream production rates. Within the multi-plant scenario, a number of 26 industrial plants each operating at throughputs of 3,330 kg/h – within the plateau operation region at the point of minimum energy consumption – would be required to satisfy the UK annual demand. Detailed operating conditions, streams, and equipment sizes for the multi-plant scenario are given in the Supplementary Material (Tables A.7 and A.8 in the Supplementary Material).

3.4.1 Effect of production scales on the unit cost.

The cost of manufacturing a kilogram of ice-cream in a single factory is the cheapest (3.13 $/kg) of all the six production scales. However, MP shows a small increase of 15 % in manufacturing costs, which suggests it might be more profitable due to the transportation and storage cost saving linked to decentralisation (Srai et al., 2016).

The opposite, i.e. higher unit costs, resulted from artisan scales, which mainly caused by the higher raw material retail prices. DM franchise model gives the lowest artisan unit cost (7.49 $/kg), increasing by 14 % when more centralised management is assumed. HM shows similar unit costs (7.59 $/kg), while FI adds the rent of facilities and equipment.

3.4.2 Net Profit

In this UK demand scenario, the average market price is kept constant for all the scales in the Net Profit calculation. Results show annual profit (after taxes and for a single facility) of 21.9 k$/year for HM, 50.2 k$/year for FI and 298.1 k$/year for DM (franchise model), decreasing by 22.3% for the case of high management costs. Figure 5(a) shows the variation of the net profit Π_{fac} for the two selling formats of premium ice cream and the two flavours (chocolate and vanilla) of standard ice cream considered in this work. This graph presents uncertainties (e.g. fluctuation of raw materials and/or energy prices) as error bars. When premium ice cream is sold in a smaller format, i.e. 150 ml, the higher increase in selling price rather than production cost results in tripling the profits. On the other hand, standard ice cream is only profitable for both flavours at FI scenario, while only vanilla flavour gives a negligible profit in DM franchise model (2.7 k$/year) - chocolate ice cream is slightly more expensive to produce.

Industrial manufacturing scales give the most profitable option due to the low manufacturing cost achieved. After estimating that a 21% of the retail's price is kept as supermarket benefit (Chidmi and Murova, 2011), SP profit in a UK scenario increases to $1.3 G billion, while for MP comprising 26 plants is $47.7 million per manufacturing plant. However, the profitability of the small-scale business might be enough to attract freelances and entrepreneurs –e.g. 21.9 k$ facility^{-1} year^{-1} after taxes for Home Manufacture (HM). All these profits have been calculated under the assumption that UK's demand is fully satisfied by selling only premium ice cream in packages of 500 ml.

3.4.3 Carbon footprint analysis of manufacturing

A breakdown of the energy use per unit operation is presented in Figure 5(b) by a bar chart comparing all the manufacturing methods. In absolute numbers, a single plant (SP) scenario demands 0.98 MJ/kg of ice cream manufactured, while a network of industrial plants (i.e. MP scenario) uses 0.72 MJ/kg, the lowest energy demand scenario. Although the energy use for raw materials and final product storage increases for multiple plants in comparison to a large single plant manufacture, the lower pumping energy needed at the smaller production lines used by MP –mainly for cooling and homogenisation – leads to lower energy demand values.

For the artisan manufacturing methods, HM presents the lowest power demand, 1.15 MJ/kg, showing that freezing small batches on a kitchen scale is more energy effective. The 3-in-1 freezer used in FI processing increases its power demand to 1.28 MJ/kg (11% more than for HM). Finally, modular manufacture represented by DM scales are the most energy intensive methods (1.78 MJ/kg), according to results shown in Figure 5(b). The choices of freezing and chilling equipment (i.e. use of blast freezer for hardening, and chilling and freezing cabinets for storage) is behind the increase in the power demand for DM scenarios.

4. Conclusions

Five different manufacture scenarios for ice cream production - i.e. Multi-Plant (MP), Single-plant (SP), Distributed Manufacturing (DM), Food Incubator (FI) and Home Manufacturing (HM) have been assessed both in economic and environmental (i.e. carbon footprint) terms. A model-based approach that took into account different levels of complexity (i.e. different ice-cream formulations, number of unit operations or production lines,) and uncertainty sources (e.g. fluctuation of raw materials and/or energy prices) was used, and the throughput range of application for each manufacturing scale was identified: Home Manufacture (HM) was found to be the most profitable scenario for ice-cream production below 45 kg/h, while Food Incubator (FM) resulted in higher production costs at a similar operation range; Distributed Manufacture (DM) with franchise management generated higher profits for throughputs between 45-650 kg/h; for larger production rates. i.e. 650-3325 kg/h, Single-Plant (SP) scenarios - assuming one line per plant - took full advantage of economies of scale reducing unit costs and increasing net profits, while Multi-Plant production (MP) became profitable above 3325 kg/h. At all scales, profitability was increased by producing a higher quality variety in smaller packages (i.e. premium ice cream in 150ml packages), while only production at industrial scale returned substantial benefits for standard ice cream manufacture.

In addition, a scale of production designed to satisfy UK's annual demand of ice cream was analysed. Results for this case study showed that Single Plant production could satisfy UK's demand levels at lowest costs, although a Multi-Plant (MP) scenario (i.e. 26 manufacture plants) could achieve similar production costs with higher energy efficiency and lower carbon footprint.

Artisan manufacturing scales (i.e. HM, FI and DM) could not compete in cost with industrial processing, mainly due to the increased retail price of raw materials, but estimated profitability for these small-scale scenarios might be enough to attract freelances and entrepreneurs. The lowest energy demand (1.15 MJ/kg) and carbon footprint (0.132 kgCO2e kg^{-1}) of the artisan methods corresponded to Home Manufacture, with values close to those of industrial production.

Overall, this study shows:

(i) how alternative manufacture paradigms might unfold for different scales of ice-cream processing. A number of assumptions and estimations have been made to operate the model, and this uncertainty might affect the accuracy of the final results presented. Transportation costs have not been considered - these will be significant for frozen products - nor has formal process/scheduling optimisation been attempted. However, this work demonstrates that such limitations are not an impediment to obtain realistic trends across wide ranges of processing scales.

(ii) the suitability of the framework to assess the scale effect in food processing. The method was initially developed for a simple dry-mix food product. With ice cream, we showed that it can also be successfully applied to more complex foods and process lines.

The work thus shows how different manufacturing scales can be compared, and sets the basis for a larger study to consider the impacts of decentralisation across the whole cold supply chain - i.e. including complexities such refrigerated transportation and storage costs, as well as the mixes of products (i.e. variants) and optimal production scheduling. Such studies are needed if alternatives to current production models are to be sought.

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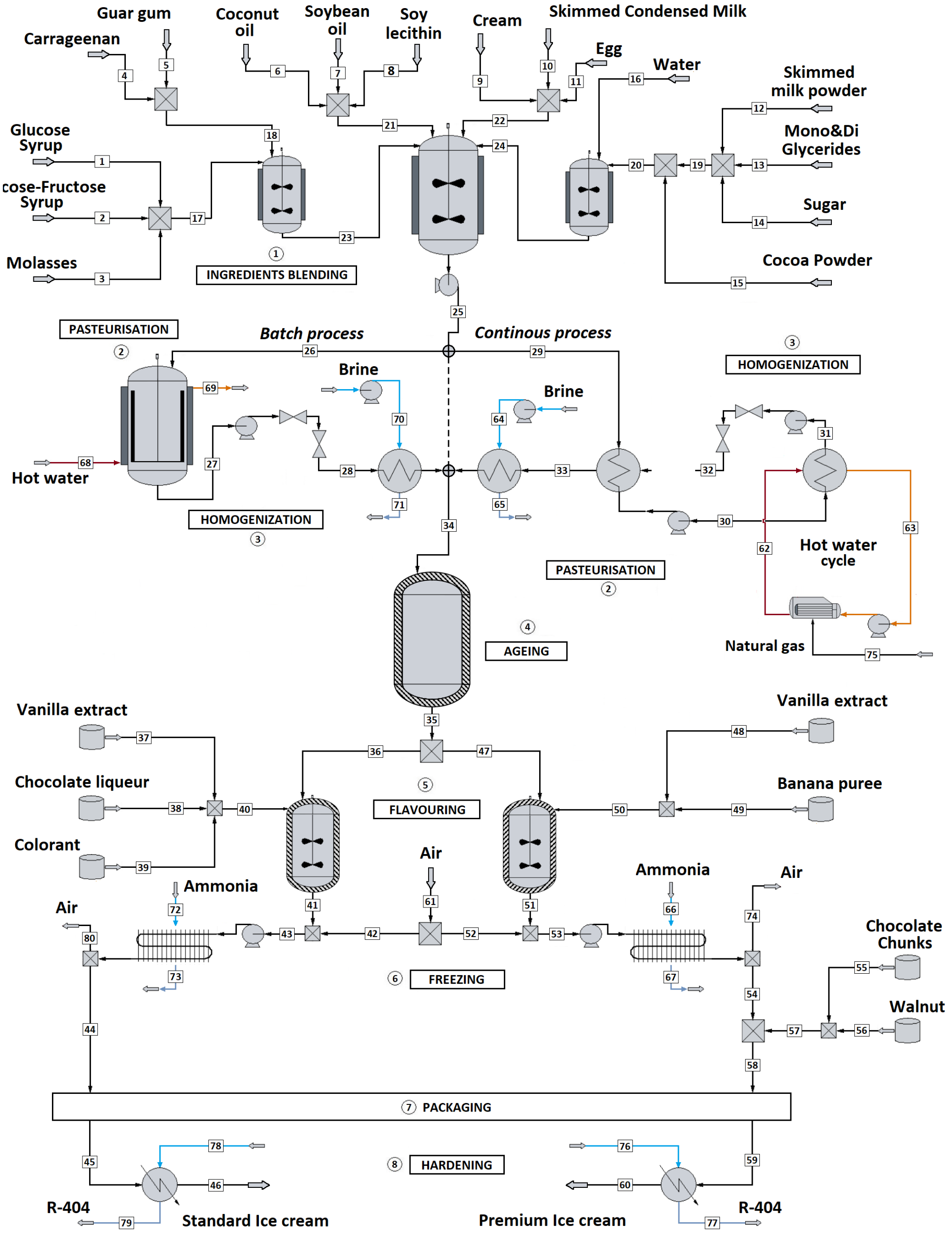


Figure 1-. Ice cream plant production flow sheet depicting all the steps of the industrial process. Both batch and continuous pasteurisation alternatives are shown.

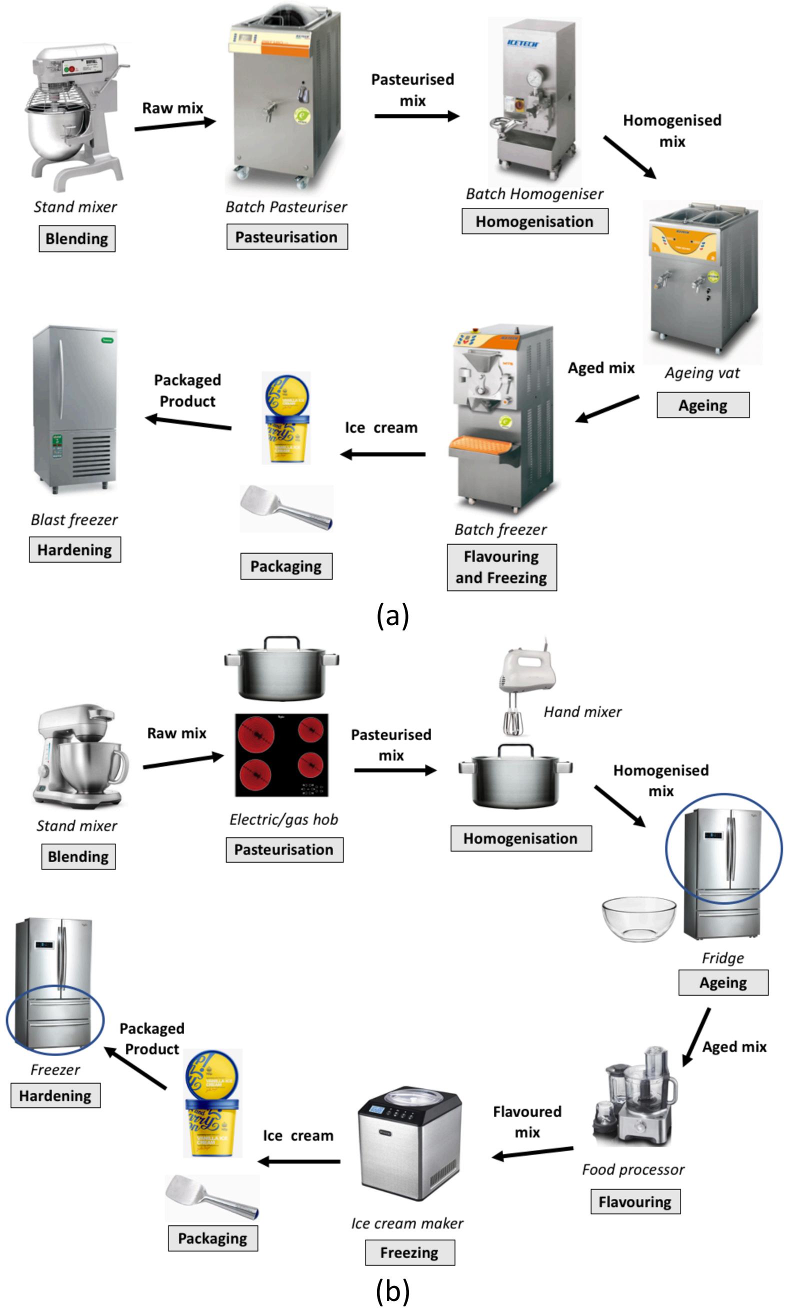
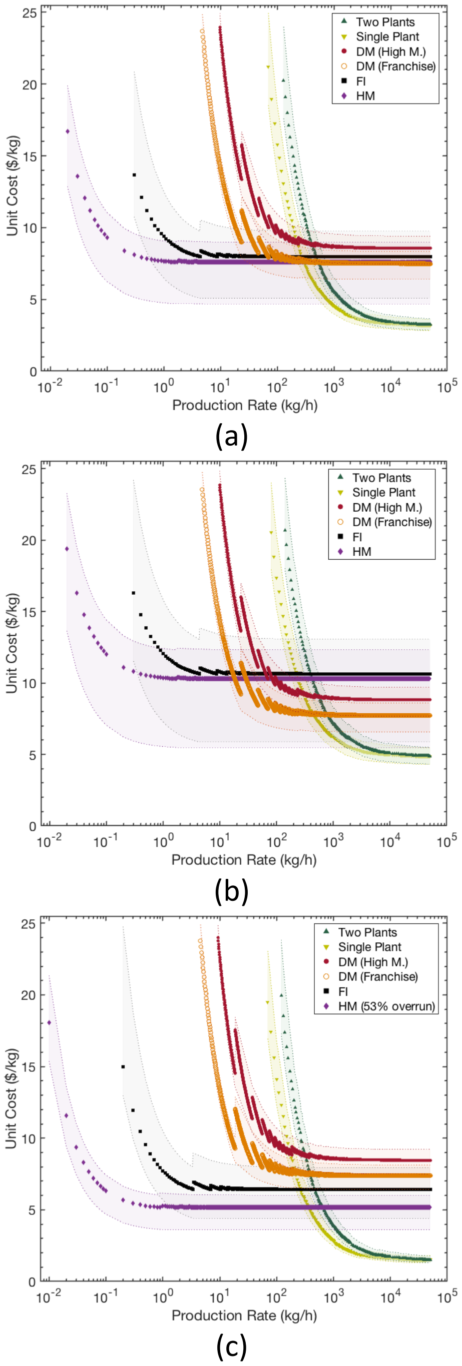


Figure 2.- Artisanal manufacture flow chart for (a) Distributed Manufacturing (DM) and (b) Food Incubator (FI) and Home Manufacturing (HM). The industrial unit operations were down-scale as domestic kitchen batch processes.

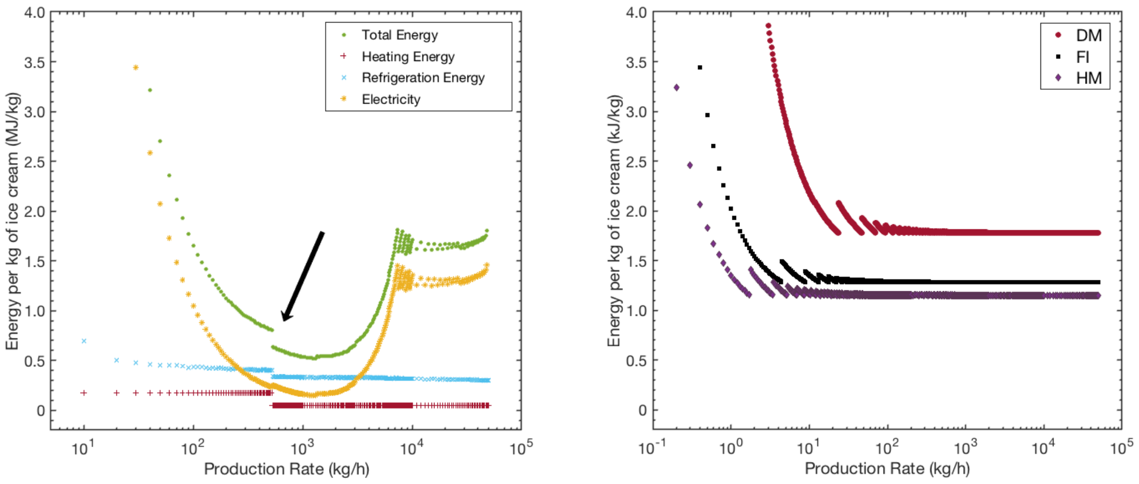


(a)

(b)

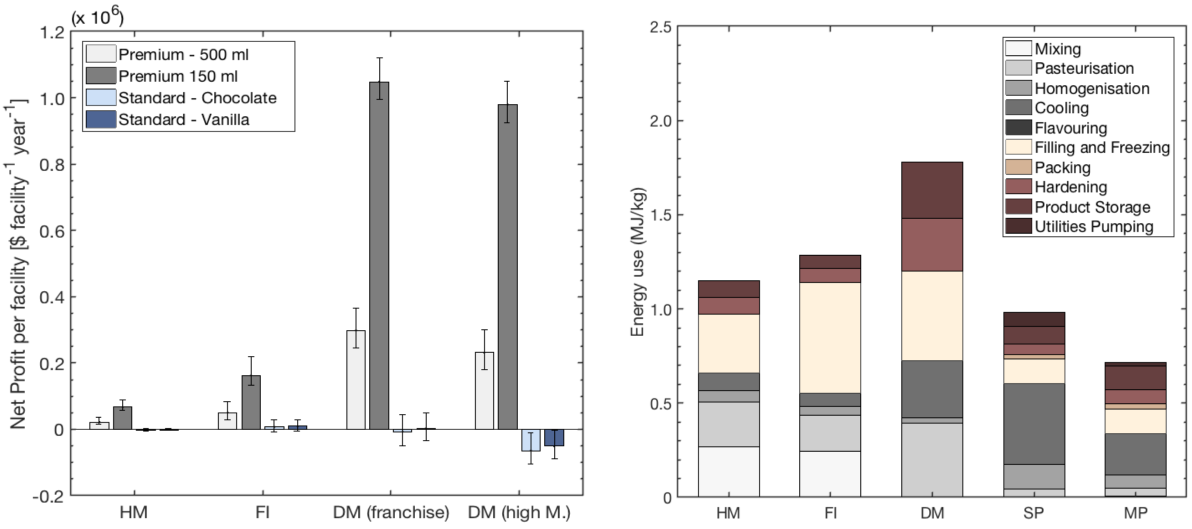
(c)

Figure 3.- Variation of the unit cost ($/kg) for different manufacturing scales: (a) premium ice cream sold in 500 ml packages (b) premium ice cream sold in 150ml packages and (c) standard ice cream sold in 1000ml packages. Shaded areas represent the trust region set by the uncertainties.



(a) (b)

Figure 4.- (a) Energy consumption for a single plant (SP) scenario. The number of four lines is randomly chosen to show the effect of splitting production in the energy demand. A discontinuity - pointed out with an arrow - appears when the process shifts from batch to continuous pasteurisation, which enables heat regeneration. (b) Energy consumption for HM, FI and DM. The integer constraints for processing equipment cause discontinuities in the energy plot. Minimum consumption is achieved when operating at full capacity.



(a) (b)

Figure 5.- Analysis of all manufacturing scales in a UK demand scenario: (a) Net profit per facility for the artisan manufacturing scales. The effect of the product formulation and the selling format is plotted in this figure. (b) Total energy consumed per kg of ice cream manufactured.

Table 1.- Standard and premium ice cream ingredients composition. Carbohydrates are estimated by difference, according to the data sources.

Standard Ice cream

Stage	*Ingredient*	*Mass fraction*	*Composition (%)* *Fat*	*Protein*	*Carbohydrate*	*Water*
Mixing (Chocolate & Vanilla)	Coconut oil	0.150	100.0	-	-	-
	Skimmed milk powder	0.120	0.7	36.0	60.3	3.0
	Sugar	0.100	-	-	98.2	1.8
	Glucose Syrup	0.030	-	-	80.3	19.7
	Glucose-Fructose Syrup	0.020	-	-	76.0	24.0
	Guar gum	0.002	-	-	90.0	10.0
	Carrageenan	0.001	0.4	0.6	89.0	10.0
	Mono glycerides	0.002	100.0	-	-	-
	Water	0.545	-	-	-	100.0
Flavouring (Chocolate)	Colorant solution	0.002	-	-	3.0	97.0
	Cocoa Powder (in mix)	0.030	13.7	19.6	63.7	3.0
	Chocolate liquor	0.050	49.0	14.0	31.0	6.0
Flavouring (Vanilla)	Colorant solution	0.002	-	-	3.0	97.0
	Vanilla extract	0.003	0.1	0.1	47.2	52.6

Premium Ice cream

Stage	*Ingredient*	*Mass fraction*	*Composition (%)* *Fat*	*Protein*	*Carbohydrate*	*Water*
Mixing	Cream	0.250	35.0	2.1	8.3	54.6
	Coconut oil	0.022	100.0	-	-	-
	Soybean oil	0.022	100.0	-	-	-
	Condensed Skim. milk	0.272	-	11.1	18.9	70.0
	Sugar	0.100	-	-	98.2	1.8
	Molasses	0.060	0.1	-	78.0	21.9
	Guar gum	0.002	-	-	90.0	10.0
	Carrageenan	0.001	0.4	0.6	89.0	10.0
	Egg yolk powder	0.010	61.3	30.5	3.5	4.7
	Soya lecithin	0.002	53.3	1.0	44.7	1.0
	Water	0.259	-	-	-	100.0
Flavouring	Banana puree	0.075	1.1	0.4	22.2	76.3
	Vanilla extract	0.003	0.1	0.1	47.2	52.6
Chunks addition	Chocolate chunks	0.085	42.9	7.1	47.6	2.4
	Walnut	0.055	59.3	24.1	12.0	4.6

Table 2.- Unit operations, operating conditions and equipment used for industrial (continuous and batch) manufacturing processes.

Stage	Equipment		Main Operating Conditions	
	Continuous	**Batch**	**Continuous**	**Batch**
Blending	High shear blender Stirred tanks	Jacketed stirred tank	$T_{room} = 25\ °C$ 15 min	$T_{past} = 69.4\ °C$ $t_{past} > 30$ min
Pasteurisation	Plate heat exchanger		$T_{past} = 79.4\ °C$ $t_{past} > 15$s	
Homogenisation	2 stage homogeniser		${P_h}^{stage1} = f(x_{fat})$ ${P_h}^{stage2} = 3.5\ MPa$ T_{past}	
Cooling	Plate heat exchanger		$T_{in} = T_{past}$; $T_{out} = T_{ageing}$	
Aging	Insulated storage vessel		$T_{ageing} = 4\ °C$ $6h < t_{ageing} < 72h$	
Flavour and and colour adding	Stirred tank		T_{ageing} 15 min	
Freezing	Scraped Surface Heat Exchanger		$T_{freezing} = -6\ °C$ Air incorporation (overrun)	
Particle addition	Inline solids feeder		$T_{freezing}$	
Packaging	Packing Machine		$T_{freezing}$	
Hardening	Hardening Tunnel		$T_{hardening} = -25\ °C$	

Table 3.- Unit operations and equipment used for artisan (batch) manufacturing processes.

Stage	**Distributed Manufacturing**		**Food Incubator**		**Home Manufacturing**	
Blending	Stand mixer	P = 1,200 V= 0.020 p = 1,400	Stand mixer	P = 1,200 V= 0.005 p = 260	Stand mixer	P = 1,200 V= 0.005 p = 260
Pasteurisation	Batch pasteuriser	P = 2 x 6,500 V= 0.120 p = 32,600	Pot/electric hob	P = 1,800 V= 0.005 p = 400	Pot/electric hob	P = 1,800 V= 0.005 p = 400
Homogenisation	Batch homogeniser	P = 13,500 $\dot{V}$= 0.100 (m^3/h) p = 5,000	Hand mixer	P = 0,800 p = 55	Hand mixer	P = 0,800 p = 55
Cooling	Ageing vat	P = 2 x 1,500 V= 0.240 p = 24,200	Fridge chiller	P = 433 (kWh/year) V= 0.364 p = 600	Fridge chiller	P = 433 (kWh/year) V= 0.364 p = 600
Ageing						
Flavour and and colour adding	Batch freezer	P = 10,000 V= 0.015 $\dot{M}$= 67.5 (kg/h) p = 40,200	3-in-1 ice cream machine	P = 12,000 V= 0.015 $\dot{M}$= 67.5 (kg/h) p = 46,250	Food processor	P = 800 V= 0.002 p = 55
Freezing					Ice cream maker *(Standard / Premium)*	P = 180 / 300 V= 0.0015 (both) t_{freez}= 35 / 20(min) p = 260 / 1100
Particle addition	*(Batch freezer's solid feeder)*		*(3-in-1 machine's solid feeder)*			
Packaging	Spatula		Spatula		Spatula	
Hardening	Blast freezer	P = 3,500 V= 0.090 $\dot{M}$= 50.0 (kg/h) p = 28,600	Fridge Freezer	P (shared with fridge) V= 0.192 m^3	Fridge Freezer	P (shared with Fridge) V= 0.192 m^3
Storage	Cabinet freezer	P = 989 (kWh/yea V= 0.620 p = 600				

Table 4.- Expressions used for the modelling of thermal properties of the ice cream. Individual food component (j) properties can be found in Appendix.

Initial freezing point –T_{IF}– (Tharp and Young, 2013)

$$T_{IF} = 9.4915 \times 10^{-5} \left(\frac{\sum x_k \frac{M_{sucrose}}{M_k} \times 100}{x_w} \right)^2 + 6.1231 \times 10^{-2} \left(\frac{\sum x_k \frac{M_{sucrose}}{M_k} \times 100}{x_w} \right) + \frac{x_{MSNF} \times 2.37}{x_w} \qquad \text{Eq.1}$$

Ice weight fraction –x_{ice}– (Miles et al., 1983):

$$x_{ice}(T) = x_w \left(1 - \frac{T_{IF}}{T} \right) \qquad \text{Eq.2}$$

Specific Heat –c_p– (Cogné et al., 2013a; Kumano et al., 2007)

$$c_p = \sum_j x_j c_{p_j} - L_f(T_{IF}) \frac{dx_{ice}}{dT}; \; L_f = 333.8 + 2.1165\, T \qquad \text{Eq.3}$$

Density –ρ– and volume fraction –ε–

$$\frac{1}{\rho_{mix}(T)} = \sum_j \frac{x_j}{\rho_j(T)} \qquad \text{Eq.4}$$

$$\varepsilon_j(T) = \frac{x_j\, \rho_{mix}(T)}{\rho_j(T)} \qquad \text{Eq.5}$$

Thermal conductivity –λ–

(Carson, 2006; Green and Perry, 2008; Renaud et al., 1992; Cognè et al., 2013)

Continuous phase

$$\lambda_{cont} = \sum_j \varepsilon_j\, \lambda_j \qquad \text{Eq.6}$$

Non aerated mix

$$\lambda_{mix}{}^{non-air} = \lambda_{cont} \frac{1 - \varepsilon_{ice} + \varepsilon_{ice}\, F\, \frac{\lambda_{ice}}{\lambda_{cont}}}{1 - \varepsilon_{ice} + \varepsilon_{ice}\, F} \qquad \text{Eq.7}$$

Factor shape

$$F = \frac{1}{3} \sum_{l=1}^{3} \left[1 + \left(\frac{\lambda_{ice}}{\lambda_{cont}} - 1 \right) f_{shape_i} \right]^{-1} \qquad \text{Eq.8}$$

$$\sum_{l=1}^{3} f_{shape_i} = 1 \quad ; \quad f_{shape_1} = f_{shape_2} = \frac{1}{11} \quad ; \quad f_{shape_3} = 9/11$$

Aerated mix

$$\lambda_{ic} = \lambda_{mix}{}^{non-air} \frac{1 - \varepsilon_{air}\, \lambda_{mix}{}^{non-air}}{1 + {}^{\varepsilon_{air}}/_{2}} \qquad \text{Eq.9}$$

Overrun – Ov_{ic}– (VanWees and Hartel, 2018)

$$Ov_{ic} = \frac{V_{ice\ cream}{}^{aerated} - V_{mix}{}^{non-aerated}}{V_{mix}{}^{non-aerated}} \times 100 \qquad \text{Eq.10}$$

Table 5.- Expressions used to model the ice cream viscosity.

Viscosity –μ_{app}–

$$\mu_{app} = K \, \dot{\gamma}_{app}{}^{n-1}$$ Eq.11

Consistency index –K– and flow behaviour exponent –n– (Arellano et al., 2013a; Hernández et al., 2018)

For: $T \geq T_{IF}$ $\quad K_{mix} = 0.5838\,;\; n_{mix} = 0.55$

For: $T < T_{IF}$ $\quad K_{ic} = 0.5838 + 10.16(T_{IF} - T)$

$$n_{ic} = n_{mix}\left[(1-\alpha) + \alpha \, exp\left(\frac{-\varepsilon_{v,ice}}{\beta}\right)\right]$$ Eq.12

Shear rate – $\dot{\gamma}$ –

Flow in pipes (simplified Rabinowitsch–Mooney equation)

$$\dot{\gamma}_{wall} = \left(\frac{3n_{ic}+1}{4n_{ic}}\right)\left(\frac{4\,\dot{V}}{\pi\, r_i{}^3}\right)$$ Eq.13

SSHE (Fredrickson and Bird, 1958; Leuliet et al., 1986)

$$\dot{\gamma}_{app} = 3.213 \times 10^4 .\, 1.45^{N_{blades}}\, n_{ic}{}^{-0.7115}\, \dot{V}_{liquid} + 23.44\, \dot{V}_{liquid}{}^{-0.03}\, n_{ic}{}^{0.1754}\, \omega_{SSHE}$$ Eq.14

Stirred tank (Calderbank and Moo-Young, 1959; Campesi et al., 2009)

$$\dot{\gamma}_{app} = k_t \left(\frac{4n_{mix}}{3n_{mix}+1}\right)^{\frac{n_{mix}}{n_{mix}-1}} \omega_t\,;\;\; k_t = 11.4$$ Eq.15
