

## Local and decentralised scenarios for ice-cream manufacture

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1 **Local and decentralised scenarios for ice-cream manufacture: a model-based**  
2 **assessment at different production scales**

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33 **Local and decentralized scenarios for ice-cream manufacture: a model-based**  
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38

39 **Abstract**

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

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

53

54

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

## Nomenclature

### Lowercase

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

### Uppercase

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

### 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

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

57

58

## 59 1. Introduction

60 Sustainability has become a critical factor in the design of food manufacture systems  
61 (Govindan, 2018; Rohmer et al., 2019), as the need to mitigate the environmental impacts of food  
62 processing - one of the major responsible of fossil fuels consumption and GHG emissions (FAO  
63 2017; Department for Business, Energy and Industrial Strategy , 2018 & 2019; EIA 2019; Ladha-  
64 Sabur et al., 2019) - grows more and more urgent (IPCC 2018). The current challenge lies in  
65 implementing manufacture processes that involve lower environmental damage and generate  
66 positive social impacts (e.g. higher engagement between local producers and consumers), while  
67 keeping economic competitiveness (Akbar and Irohara, 2018).

68 In this context, alternative production scenarios based on emerging “on-demand” and “sharing”  
69 models, together with distributed manufacture methods (Almena et al., 2019), are potential

70 alternatives to increase sustainability across the food supply chain. Such alternative methods are  
71 based on a restructuring of production into decentralised small-scale facilities (Sellitto et al., 2018;  
72 Jarosz, 2018; Angeles-Martinez et al., 2018), which shortens distances to consumers – thus  
73 decreasing energy use and emissions linked to product transportation and storage (Srai et al.,  
74 2016) – and/or involves more sustainable and ethical practices into the manufacturing processes  
75 (Cottee, 2014; Rauch et al., 2017). All these changes are facilitated by (i) the increasing  
76 digitalisation of the food sector, which minimises logistics cost (Kagermann, 2015; Maslarić et al.,  
77 2016) (ii) the growth of ICT (i.e. Information and Communications Technologies), which speeds  
78 up interaction between manufacturers and consumers (Miranda et al., 2019), and (iii) new  
79 manufacturing technologies, such as additive (Freeman and McMahon, 2019) and modular  
80 manufacturing (Baldea et al., 2017), which concept might be better suited for decentralised  
81 structures.

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

94 Current literature focuses mainly on modelling and/or optimisation of single stages of ice cream  
95 manufacture, such as freezing/crystallisation (Cogné et al., 2003b; Arellano et al., 2013b,2013c;  
96 Bayareh et al., 2017; Hernandez-Parra et al., 2018) or storage (Tsevdou et al., 2015). There are a  
97 few works modelling properties that depend on product formulation such as viscoelasticity  
98 (Rahman et al., 2019) or thermal properties (Cogné et al., 2003a), while environmental impact  
99 assessments of ice cream offer only lumped results for the manufacture step (Konstantas et al.,  
100 2019a and 2019b). To the best of our knowledge, the literature does not contain models for all  
101 the stages in ice cream processing, together with profitability and environmental (i.e. carbon  
102 footprint) evaluation.

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

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

117

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

123

## 124 **2. Materials and Methods**

### 125 2.1. Ice cream formulation

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

131

### 132 2.2 Manufacture methods

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

137

#### 138 *2.2.1 Industrial manufacture*

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

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

146

### 147 2.2.1 Artisanal manufacture

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

- 151 i) *Home Manufacturing (HM)*, based on domestic kitchen production (i.e. the smallest  
152 throughput per facility). This is the most decentralised manufacture method, with freelance  
153 workers following the 'gig-economy' model and selling home-made ice cream on-demand  
154 (Gleim et al., 2019).
- 155 ii) *Food incubator (FI)*, where under-utilised assets, such as specialised equipment and  
156 facilities, are rented by freelance workers to produce ice cream in an on-demand basis  
157 (Alonso-Almeida et al., 2020).
- 158 iii) *Distributed Manufacturing (DM)*, which represents a modular manufacturing approach,  
159 with small catering size facilities scattered within a region/country. This scale assumes a  
160 combination of sole proprietorship and corporation model with two management cost  
161 alternatives: *low management (franchise)* and *high management (company)*.

162

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

165

## 166 2.3 Modelling approach

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

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

178 The model can also consider different levels of complexity (e.g. number of unit operations or  
179 production lines) and uncertainty sources (e.g. fluctuation of raw materials and/or energy prices).

180 **It was implemented and solved in Matlab, with unit operations defined as subroutines and a main**  
181 **programme calling the sequence of events as per flowsheet**. All the assumptions made for each  
182 manufacture scale are provided in the Supplementary Material.

183

### 184 2.3.1 Modelling assumptions

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

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

- 191 • Standard ice cream is sold in one litre cups, while two formats –150 ml and 500ml– are  
192 considered for premium ice cream. Average market prices were taken from the four biggest  
193 UK supermarkets - 3.5 £/unit, 3 £/unit and 5 £/unit respectively (Tesco, 2019; Sainsburys,  
194 2019; Asda, 2019; Morrisons, 2019).- and converted into USD\$ (i.e. 4.52 \$/unit, 3.87 \$/unit  
195 and 6.47 \$/unit, respectively).
- 196 • There are no product changeovers assumed.
- 197 • Ice cream overrun for the standard ice cream is 110% and for the premium ice cream is 27%,  
198 following the cited commercial product examples.
- 199 • A waste factor of 0.1 % and 0.5 % per unit operation for the industrial and artisan processes  
200 is, respectively, accounted in the mass balances.
- 201 • Value added tax for ice cream in the UK is 20% of its market price (Government of United  
202 Kingdom, 2019a) and the Corporation tax reduction is the 19% of the Gross Profit  
203 (Government of United Kingdom, 2019b)
- 204 • Management cost was estimated following the procedure detailed in Almena et al. (2019).
- 205 • An operation mode of 5 days and 2 shifts (Maroulis and Saravacos, 2008) is assumed for the  
206 ice cream plant, allowing overnight ageing of the mix. The plant annually closes for 4 weeks  
207 to perform maintenance.
- 208 • The operation mode for HM and FI is 5 days and 1 shift, as they represent a freelance worker  
209 scenario. DM replicates industrial processing, operating 5 days and 2 shifts.
- 210 • For artisan scales, cleaning time of 1 h is assumed within the daily working time; for industrial  
211 production, a daily starting up time of 15 min and a cleaning time of the line of 2h were  
212 considered (Kopanos et al., 2012).
- 213 • Only one production line is assumed per facility, either artisan or industrial. For artisan scales,  
214 HM uses one piece of each equipment, FI has two items of each instrument available, and  
215 DM processing line consists of a single module per unit operation.

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

219

### 220 2.3.2 Ice cream thermophysical properties and rheology

221 Thermophysical properties (specific heat, density, thermal conductivity) are defined using mixing  
222 rules based on the recipe for the different formulations (see Table 4 for a complete description).  
223 For each one of the main constituents (water, protein, fat, carbohydrate, fibre and ash) those  
224 properties are defined as temperature dependent functions using formulae from Choi and Okos  
225 (1986) formulae (Table A.1 in Supplementary Material). Equations used to define the ice-cream  
226 freezing point depression, ice fraction and overrun are also given in Table 4. The expressions  
227 used to characterise the viscosity of the ice-cream along the different stages of the manufacturing  
228 process (pre-frozen and frozen mixes) and through the different pieces of equipment are listed in  
229 Table 5.

230

### 231 2.3.3. Process modelling

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

237

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

240

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

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

247

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

254

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

258

#### 259 *2.3.4. End-use energy demand and carbon footprint evaluation*

260 For artisan manufacture (HM, FI and DM), the process is fully electric and the energy use per  
261 batch is calculated from the sum of the power consumption of each piece of equipment (as per  
262 technical specifications). At industrial scales (SP and MP), processing equipment (including  
263 pumps and cooling/freezing devices) uses electricity, while auxiliary water heating (e.g. for

264 pasteurisation) used a boiler fuelled by natural gas. Experimental correlations used to calculate  
265 electric power requirements as well as the expression used to calculate the energy supply to the  
266 boiler can be found in the Supplementary Material. The carbon footprint of the process given as  
267 GHG emissions was computed using energy demand by source and conversion factors in  
268 Government of United Kingdom (2019c).

269

### 270 2.3.5. Economic evaluation

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

280

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

281

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

285

## 286 3. Results and Discussion

### 287 3.1 Unit cost at multiple manufacturing scales

288 A comparison of unit costs per kilogram of product for the five manufacturing models –HM, FI,  
289 DM, SP and MP– is presented in Figure 3(a). All the manufacturing scenarios were modelled  
290 across a production rate ranging from 0.01 kg/h to 50,000 kg/h, with maximum capacities per  
291 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  
292 packages of 500 ml at a market price of 12.4 \$/kg, was chosen as the reference product for this  
293 comparison. For all methods, the cost curves can be divided in three regions:

294

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

301

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

308 Producing smaller packs of ice cream results in higher unit costs for all scales, as can be seen by  
309 comparing unit costs for 500 ml packages in Figure 3(a) to cost data presented in Figure 3(b) for  
310 150 ml packages. For example, production costs rise 50% and packaging cost increases by 6  
311 times for industrial scales producing the smaller format, while for artisan-based scales, the unit  
312 cost for both HM and FI scales increases above DM costs because of higher management fees

313 for the latter, which have been calculated as a multiplier of sales revenue following the 'gig  
314 economy' model.

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

323

### 324 3.2 Influence of the manufacturing scale on the total capital and labour

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

336 reached. If the production is divided in two operating plants, the total capital follows a parallel  
337 trend to SP, with an averaged addition of \$8 million.

338

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

346

347 3.3 Energy consumption of industrial and artisan manufacturing processes.

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

359

360 Artisan-based manufacturing scales, which are fully electric powered, show a constant value of  
361 specific energy consumption for production capacities above 100 kg/h, as shown in Figure 4(b).  
362 At lower volumes, discontinuities are seen due to the addition of new facilities with non-full storage  
363 units. HM proves to be the most energy effective of the artisanal scales (1150 kJ/kg), followed by  
364 FI that uses 10% more. DM requires 1780 kJ of electricity per kg of ice cream produced, thus  
365 increasing the energy demand of the artisan process by 55%.  
366 Energy consumption for ice cream production has been reported within 1.90 and 3.70 MJ/kg  
367 (Ladha-Sabur et al., 2019). If only ice cream manufacture is considered – assuming that the raw  
368 materials are bought ready-to-use and they do not require any transformation that adds up to  
369 energy demand – the overall energy consumption decreases to 0.70 MJ/kg (Foster et al., 2006;  
370 Fisher et al., 2013). This indicates that significant energy demand reductions are achievable by  
371 the industrial scales operating with more than one production line/plant, since the energy use  
372 minimum (*ca.* 0.6 MJ/kg) shifts towards the region of profitable production rates ( $>10^4$  kg/h, as in  
373 Figure 3) when the number of lines/plants increases. On the other hand, the three artisan scales  
374 can duplicate (HM and FI) or even triplicate (DM) industrial energy demands when operating at  
375 profitable production rates (1-100 kg/h, as in Figure 3).

376

### 377 *3.4 Case study: UK ice-cream demand scenario.*

378 This section presents an analysis of possible different manufacture scales for an ice-cream  
379 production scenario based on UK annual demand, which was approx. 328M litres in 2018 (ONS,  
380 2019). According to this, a production rate of 86,500 kg/h (considering the industrial operation  
381 mode) is needed to satisfy the UK demand. Assuming that the demand is satisfied by selling only  
382 premium ice cream in packages of 500 ml, the UK supplied by a HM model would comprise 49,744  
383 scattered facilities over the country, employing an equivalent number of individuals. FI would  
384 reduce this number to 19,630 facilities, due to an increase in the production per facility and worker.

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

391

#### 392 *3.4.1 Effect of production scales on the unit cost.*

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

397 The opposite, i.e. higher unit costs, resulted from artisan scales, which mainly caused by the  
398 higher raw material retail prices. DM franchise model gives the lowest artisan unit cost (7.49 \$/kg),  
399 increasing by 14 % when more centralised management is assumed. HM shows similar unit costs  
400 (7.59 \$/kg), while FI adds the rent of facilities and equipment.

401

#### 402 *3.4.2 Net Profit*

403 In this UK demand scenario, the average market price is kept constant for all the scales in the  
404 Net Profit calculation. Results show annual profit (after taxes and for a single facility) of 21.9  
405 k\$/year for HM, 50.2 k\$/year for FI and 298.1 k\$/year for DM (franchise model), decreasing by  
406 22.3% for the case of high management costs. Figure 5(a) shows the variation of the net profit  
407  $\Pi_{fac}$  for the two selling formats of premium ice cream and the two flavours (chocolate and vanilla)  
408 of standard ice cream considered in this work. This graph presents uncertainties (e.g. fluctuation  
409 of raw materials and/or energy prices) as error bars. When premium ice cream is sold in a smaller

410 format, i.e. 150 ml, the higher increase in selling price rather than production cost results in tripling  
411 the profits. On the other hand, standard ice cream is only profitable for both flavours at FI scenario,  
412 while only vanilla flavour gives a negligible profit in DM franchise model (2.7 k\$/year) - chocolate  
413 ice cream is slightly more expensive to produce.

414 Industrial manufacturing scales give the most profitable option due to the low manufacturing cost  
415 achieved. After estimating that a 21% of the retail's price is kept as supermarket benefit (Chidmi  
416 and Murova, 2011), SP profit in a UK scenario increases to \$1.3 G billion, while for MP comprising  
417 26 plants is \$47.7 million per manufacturing plant. However, the profitability of the small-scale  
418 business might be enough to attract freelancers and entrepreneurs –e.g. 21.9 k\$ facility<sup>-1</sup> year<sup>-1</sup>  
419 after taxes for Home Manufacture (HM). All these profits have been calculated under the  
420 assumption that UK's demand is fully satisfied by selling only premium ice cream in packages of  
421 500 ml.

422

### 423 3.4.3 Carbon footprint analysis of manufacturing

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

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

436 (i.e. use of blast freezer for hardening, and chilling and freezing cabinets for storage) is behind  
437 the increase in the power demand for DM scenarios.

438

#### 439 **4. Conclusions**

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

456

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

461 Artisan manufacturing scales (i.e. HM, FI and DM) could not compete in cost with industrial  
462 processing, mainly due to the increased retail price of raw materials, but estimated profitability for  
463 these small-scale scenarios might be enough to attract freelances and entrepreneurs. The lowest  
464 energy demand (1.15 MJ/kg) and carbon footprint (0.132 kgCO<sub>2e</sub> kg<sup>-1</sup>) of the artisan methods  
465 corresponded to Home Manufacture, with values close to those of industrial production.

466

467 Overall, this study shows:

- 468 (i) how alternative manufacture paradigms might unfold for different scales of ice-cream  
469 processing. A number of assumptions and estimations have been made to operate the  
470 model, and this uncertainty might affect the accuracy of the final results presented.  
471 Transportation costs have not been considered - these will be significant for frozen  
472 products - nor has formal process/scheduling optimisation been attempted. However, this  
473 work demonstrates that such limitations are not an impediment to obtain realistic trends  
474 across wide ranges of processing scales.
- 475 (ii) the suitability of the framework to assess the scale effect in food processing. The method  
476 was initially developed for a simple dry-mix food product. With ice cream, we showed that  
477 it can also be successfully applied to more complex foods and process lines.

478

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

484

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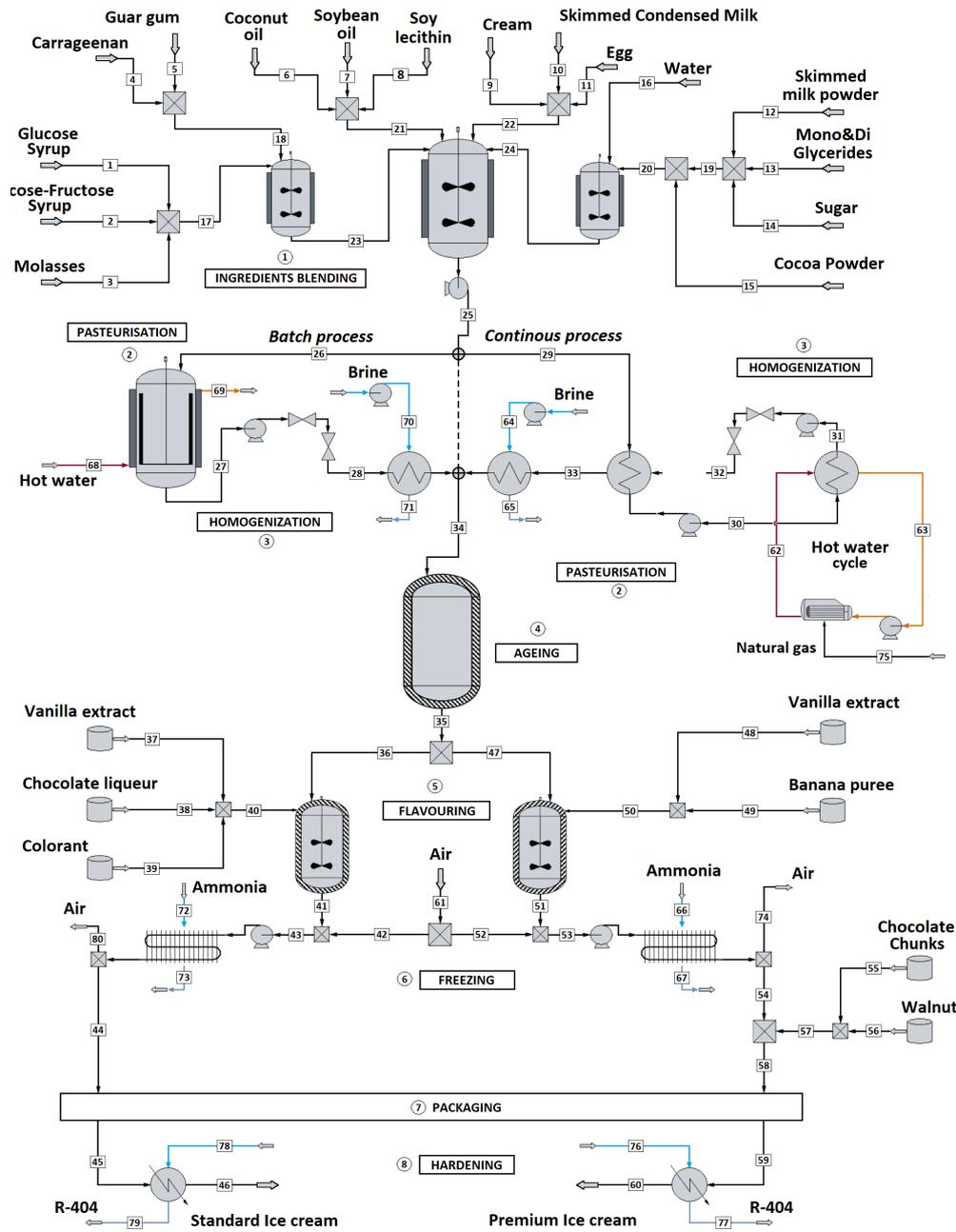


Figure 1-. Ice cream plant production flow sheet depicting all the steps of the industrial process. Both batch and continuous pasteurisation alternatives are shown.

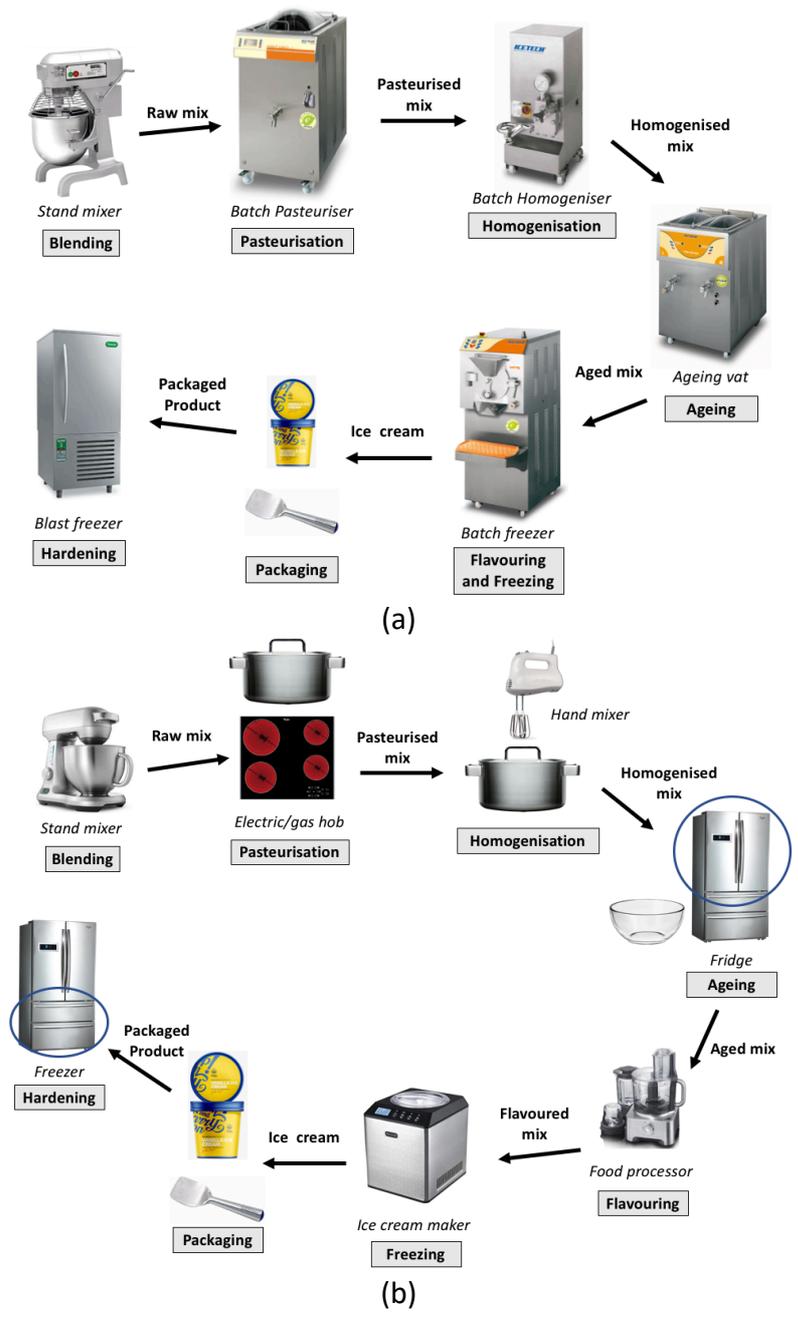
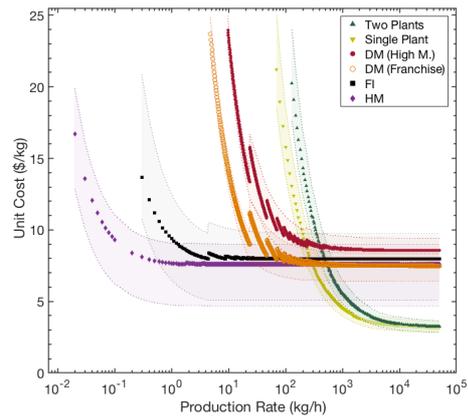
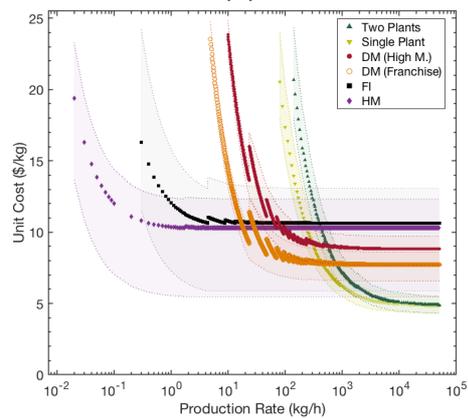


Figure 2.- Artisanal manufacture flow chart for (a) Distributed Manufacturing (DM) and (b) Food Incubator (FI) and Home Manufacturing (HM). The industrial unit operations were down-scale as domestic kitchen batch processes.

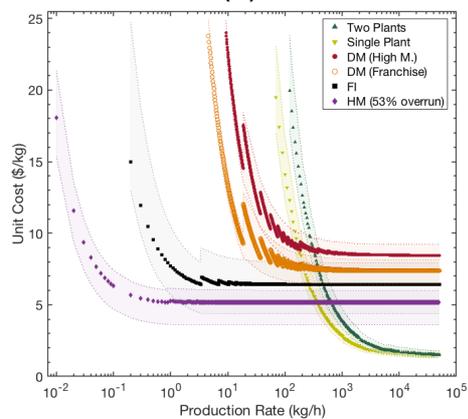
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(a)



(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.

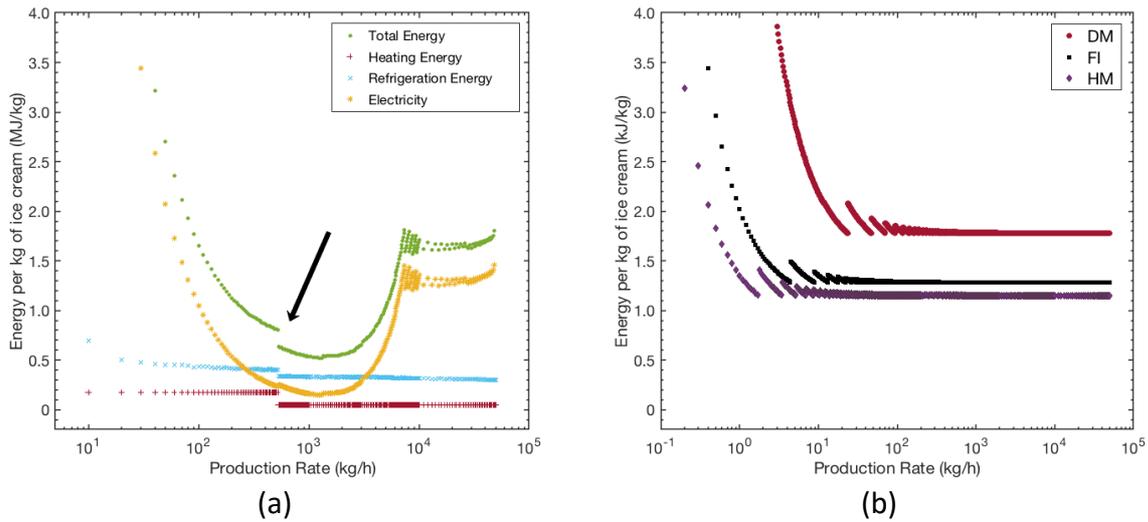


Figure 4.- (a) Energy consumption for a single plant (SP) scenario. The number of four lines is randomly chosen to show the effect of splitting production in the energy demand. A discontinuity - pointed out with an arrow - appears when the process shifts from batch to continuous pasteurisation, which 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.

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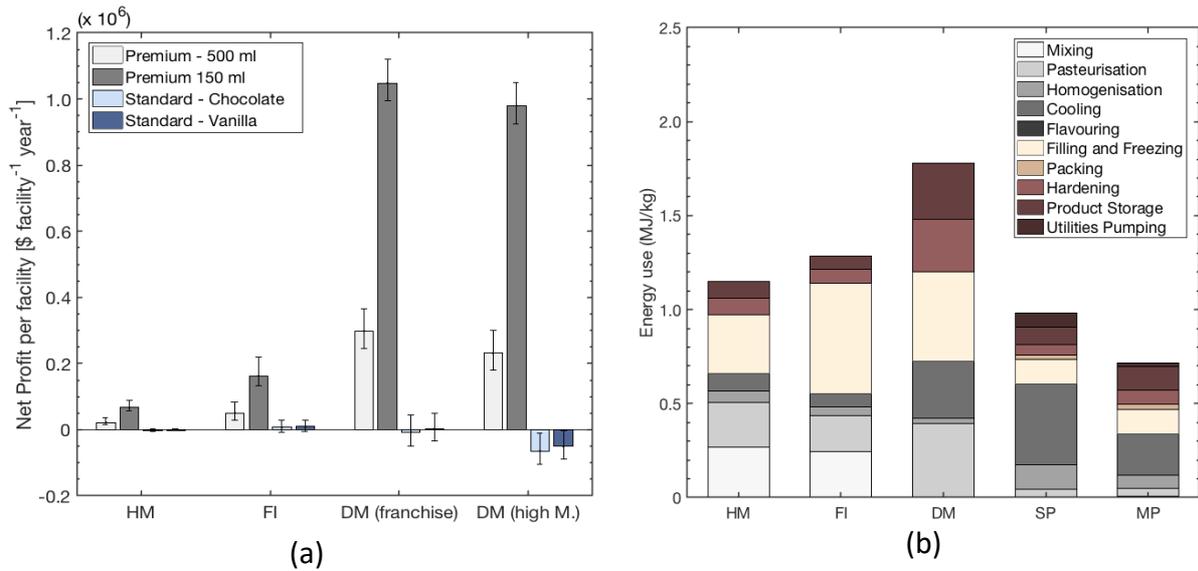


Figure 5.- Analysis of all manufacturing scales in a UK demand scenario: (a) Net profit per facility for the artisan manufacturing scales. The effect of the product formulation and the selling format is plotted in this figure. (b) Total energy consumed per kg of ice cream manufactured.

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

<b>Standard Ice cream</b>							
<i>Stage</i>	<i>Ingredient</i>	<i>Mass fraction</i>	<i>Composition (%)</i>				
			<i>Fat</i>	<i>Protein</i>	<i>Carbohydrate</i>	<i>Water</i>	
Mixing	Coconut oil	0.150	100.0	-	-	-	
(Chocolate & Vanilla)	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	
<b>Premium Ice cream</b>							
<i>Stage</i>	<i>Ingredient</i>	<i>Mass fraction</i>	<i>Composition (%)</i>				
			<i>Fat</i>	<i>Protein</i>	<i>Carbohydrate</i>	<i>Water</i>	
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	

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

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

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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)

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

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

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

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

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

**Density  $-\rho$ – and volume fraction  $-\varepsilon$ –**

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

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

**Thermal conductivity  $-\lambda$ –**

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

Continuous phase  $\lambda_{cont} = \sum_j \varepsilon_j \lambda_j \quad \text{Eq.6}$

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

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

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

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

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

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

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

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**Viscosity – $\mu_{app}$ –**

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

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

$$\begin{aligned} \text{For: } T \geq T_{IF} & \quad K_{mix} = 0.5838 ; n_{mix} = 0.55 \\ \text{For: } T < T_{IF} & \quad K_{ic} = 0.5838 + 10.16(T_{IF} - T) \\ & \quad n_{ic} = n_{mix} \left[ (1 - \alpha) + \alpha \exp\left(\frac{-\varepsilon_{v,ice}}{\beta}\right) \right] \end{aligned} \quad \text{Eq.12}$$

**Shear rate – $\dot{\gamma}$ –**

*Flow in pipes (simplified Rabinowitsch–Mooney equation)*

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

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

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

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

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


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