

Centralized and distributed food manufacture

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1 **Centralized and distributed food manufacture: A modelling platform for**
2 **technological, environmental and economic assessment at different production**
3 **scales.**

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7 **Abstract**

8 Centralized manufacturing methods have been increasingly implemented in the food
9 manufacturing sector. Proving to be more cost-efficient in terms of production, centralization
10 also involve rigid and lengthy supply chains with high both environmental and cost impacts.
11 Distributed manufacturing, based on local production at small scale, represents an alternative
12 that could provide flexibility to the currently established centralized supply chains, together
13 with environmental and social benefits. A modelling tool for the process design, evaluation
14 and comparison of different centralized and decentralized manufacturing scenarios, both in
15 economic and environmental terms, is presented in this work. The production of a dried food
16 product (cereal baby porridge) has been chosen as a case study. Three decentralized –(i)
17 Home Manufacturing (HM), (ii) Food Incubator (FI), (iii) Distributed Manufacturing (DM)– and
18 two centralized –(iv) Single Plant (SP) and (v) Multi-plant (MP)– production scales were
19 evaluated for throughput values ranging from 0.5 kg/h to 6000 kg/h, and different operational
20 regions (i.e. unfeasible, transition and plateau) were identified for each scale. A production
21 scenario using UK dry baby food demand was also studied. The most decentralized scales
22 (HM and FI) become profitable (i.e. production cost below market prices) at very low
23 production rates (e.g. 1 kg/h) that industrial manufacturing (showing a lower boundary for SP
24 profitability at 200 kg/h) cannot achieve. HM and FI remain competitive to SP at national
25 demands such as UK dimension – HM has a cost just 1% higher. DM scenarios require low
26 management costs to represent an efficient alternative to SP. Finally, for equal power source,
27 decentralized manufacture does not imply saving in energy or greenhouse gases emissions
28 (GHG) but demand more manpower.

29

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31 **Keywords:** decentralization; distributed food manufacture; energy demand; carbon footprint;
32 scale-down.

33

34 **1. Introduction**

35 At the beginning of the 18th Century, manufacturing was carried out by small facilities
36 located close to consumers. Products were developed using craft methods by artisan
37 manufacturers spread across communities. Their target market was the local neighborhood,
38 and in this way local demand was satisfied (Cipolla, 2003). The Industrial Revolution
39 established a factory system, that combined machinery with sources of power, and gathered
40 a high number of workers under supervision (Schmenner, 2010). The production of goods was
41 relocated into big facilities, achieving rise in productivity and great cost reduction. Such
42 *Centralized Manufacturing*, taking advantage of technology and economies of scale
43 (Helpman, 1981), uses a small number of very large production plants to satisfy the whole
44 demand for a good in a certain country, and possibly overseas demand via exports (Roos et
45 al., 2016). The final product must be standardized as large-scale production requires a
46 standard product for the entire market. Many regional characteristics were therefore lost.
47 These plants can be built far from the market, seeking cheaper labor and taxes. As a
48 consequence of such centralization, the concept of supply chain arises (Fahimnia et al., 2013).

49 The food Industry is the largest industry sector in the UK contributing £113 billion to the
50 economy (DEFRA, 2017). The food supply chain comprises several stages (Tassou et al.,
51 2014): i) production or farming of raw materials ii) transport of raw materials to the processing
52 facility iii) manufacture of the food product iv) distribution from manufacturers to retailers (shop
53 or restaurant) v) retail storage vi) sale. Each stage involves financial cost, energy consumption
54 and environmental impact. The UK food supply chain consumes 367 TWh every year (18% of
55 total energy) and is responsible for 147 Mt CO₂ e. emissions (15% of total associated to UK)
56 (DEFRA, 2017). Transport costs are significant.

57 Thus, a partial return to low scale manufacture situated near customers could be more
58 environmentally acceptable, minimizing transport and storage cost is the up-to-date research
59 in this field. These two attributes, i.e. small scale and location close to customers
60 (*decentralization*), set the basis for *Distributed Manufacturing* (Cottee, 2014). Drivers for this
61 change include new technologies, rising logistics costs, and changing global economies (Matt
62 et al., 2015). Figure 1 schematically shows Centralized and Distributed Manufacturing.

63 At low throughput, fixed costs become too expensive for large plants and this drives the
64 cost above the market price. The advantages of the economies of scale are lost (Ruffo et al.,
65 2015) so an alternative manufacturing system must be found. Such alternative could be
66 Artisan Manufacture. Craft production at small scale can provide fresh and trusted local food,
67 for example following traditional recipes developed by local chefs (Kuznesof et al., 1997).
68 Each local craft manufacturer can introduce variations on the product, resulting in local
69 customization (Rauch, et al, 2016). Locating manufacture close to consumers shortens the
70 supply chain, so energy use related to distribution and storage will decrease (Srai et al, 2016)
71 as well as emissions caused by transportation. Shorter supply chains can also provide fresher
72 and natural products. The brewery sector in the UK can be taken as a good example of this
73 return to artisan/craft manufacture, with a growth of 184% in the number of microbreweries
74 between 2002 and 2013 (Ellis and Bosworth, 2015).

75 Decentralization is a scale-down problem, addressing the loss of economies of scale. There
76 are few studies (Angeles-Martinez et al., 2018) on how these scenarios might unfold. In this
77 work, we proposed a model-based methodology to evaluate and compare the profitability of
78 different food manufacturing scenarios across a wide range of production scales and
79 decentralization alternatives.

80

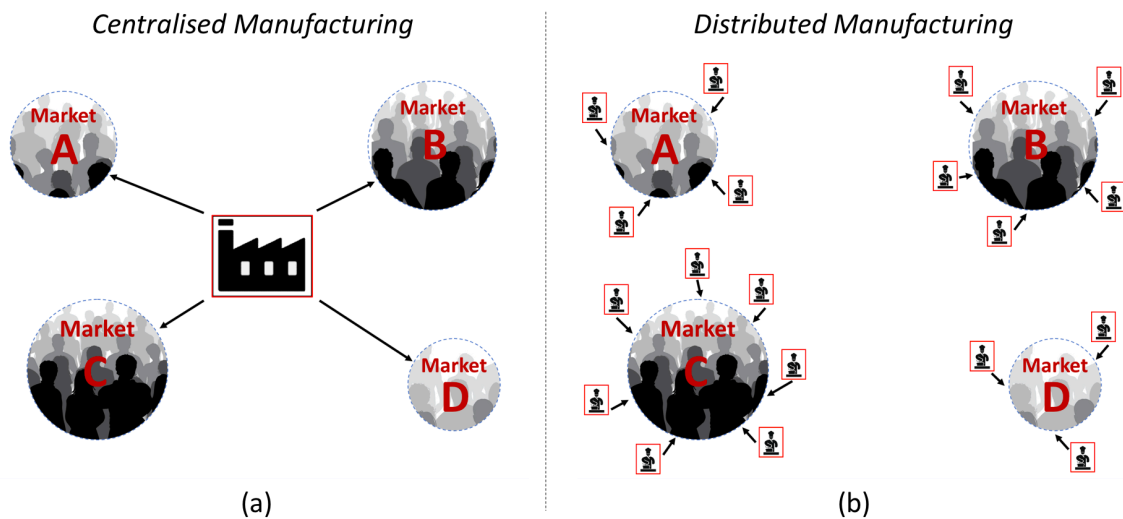


Figure 1: Food product supply chain. (a) Centralized Manufacturing (scenario A) vs. (b) Distributed Manufacturing (scenario B). A net of manufacturing facilities replaces a big plant for supplying the demand of a product in four different markets.

81

82 The basis of this methodology will be illustrated using a dry food product (dry cereal
 83 porridge, reconstitutable with the addition of water or milk). The manufacture of dried foods is
 84 energy intensive due to the heat loads required to remove all the water in the products (Ladha-
 85 Sabur et al., 2019), although transportation and storage is cheap, as no energy is required for
 86 preservation and its specific volume is low as they are dehydrated. An efficient result for dry
 87 foods would suggest profitability for products that could take more potential advantages from
 88 decentralized manufacture methods, such as refrigerated and frozen goods.

89

90 2. Characterization of different manufacturing scenarios

91 2.1. General description of the manufacture process

92 Two different manufacturing methods are considered in this work: industrial and artisanal
 93 production. The unfeasibility of industrial Table 1 lists the most representative production
 94 conditions and equipment for each case. Industrial production is based on a process line
 95 (Figure 2(a)), whilst Artisan production keeps the same unit operations but at smaller scales.

96 This requires changes in the equipment (see Figure 2(b)) and other manufacturing aspects,
 97 e.g. batch operation. Further equipment details (e.g. prices, dimensions, capacities) are
 98 provided in the Supplementary Material (see Table S.1, Table S.2 and Table S.3).

99 The result of both processes is a final product – reconstitutable dry cereal porridge – with
 100 the following composition: 35 w% oat, 11 w% rice, 30 w% milk powder, 20 w% of sugar, 3 w%
 101 of palm oil and 1 w% of malt extract, with a final 6% water content.

102

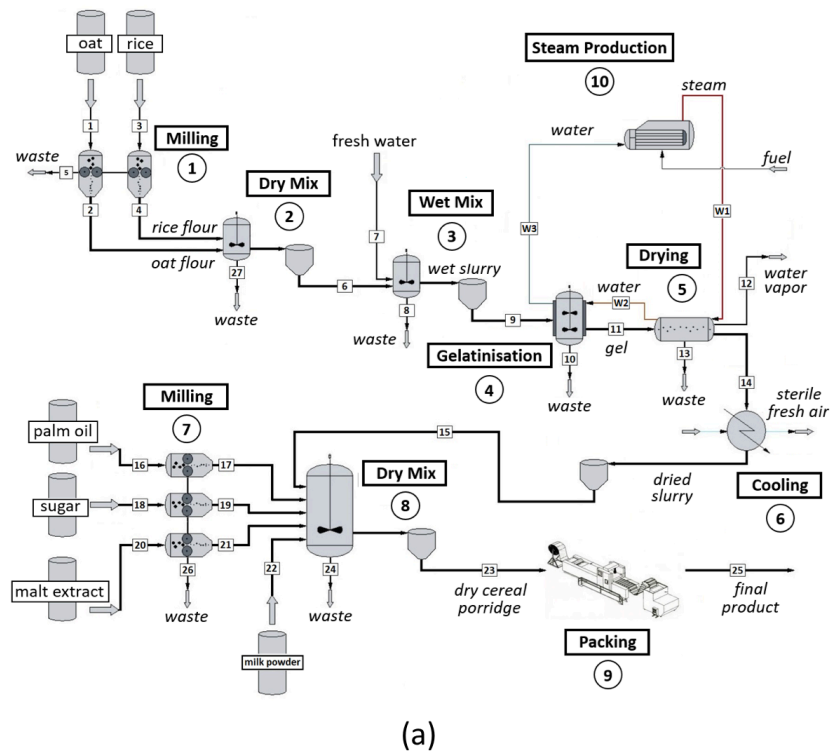


Figure 2(a): Baby food plant production flow chart depicting all the steps of the industrial process. As this is a semi-continuous process, intermediate storage tanks are used to ensure a continuous throughput. Red flow line represents heat integration.

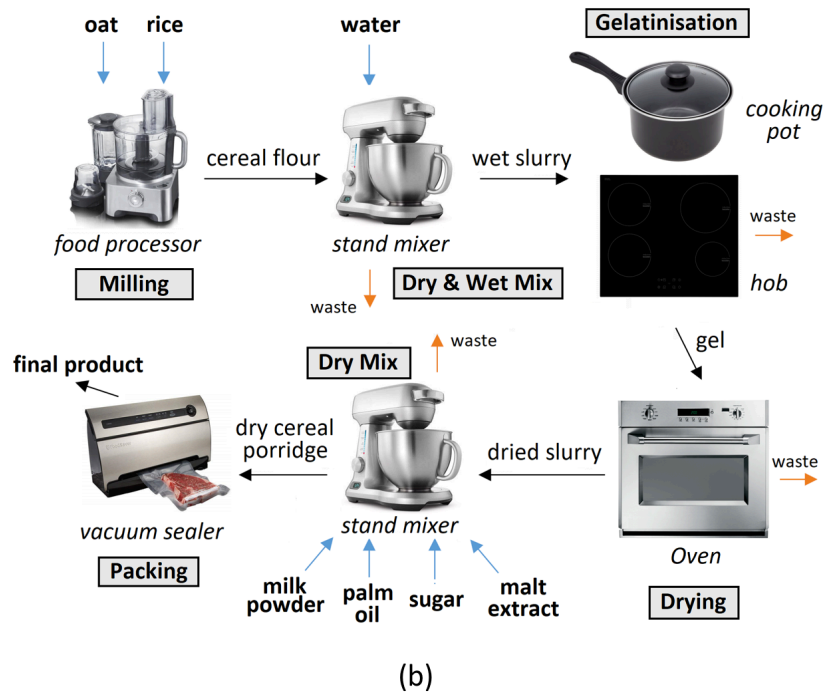


Figure 2(b): Artisanal manufacture flow chart. The industrial unit operations are adapted to be developed as a domestic kitchen batch process.

103

104 2.2. Production scenarios

105 Four different scenarios for the production of dry cereal porridge were considered, from
 106 extreme distribution to centralization, as depicted in Figure 3:

107 i) *On-demand economy*: Home Manufacturing (HM). This is based on home production,
 108 using the 'gig-economy' model (Stanford, 2017). It is assumed that a group of cooks produce
 109 the food at home (1 worker per kitchen) and sell it on-demand.

110 ii) *Sharing economy*: Food incubator (FI). This scenario can be described in terms of
 111 owners of under-utilized physical assets renting them to develop an economic activity
 112 (Frenken, 2017), e.g. Airbnb[®]. A Food Incubator can be defined as a group of cooks renting
 113 suitable premises and specialized equipment to satisfy a demand.

114

115

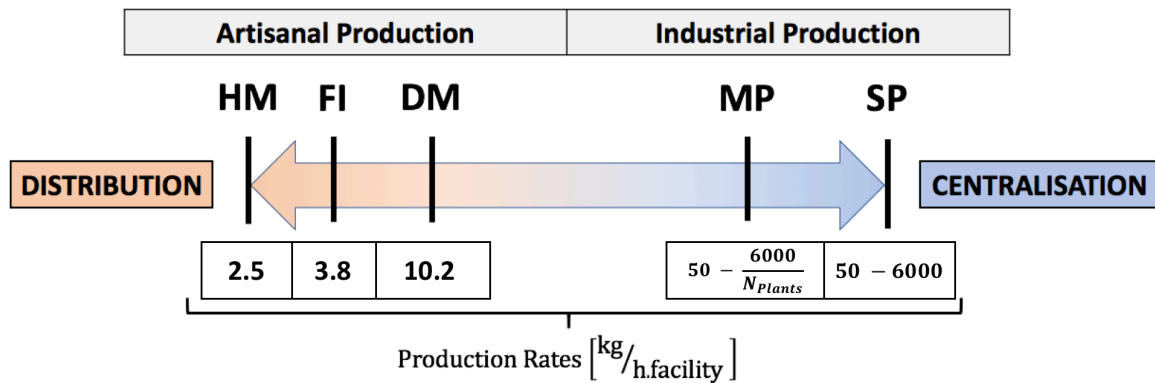


Figure 3: Schematics representing the production methods and scale considered in this work. HM: Home Manufacturing, FI: Food Incubator, DM: Distributed Manufacture, SP: Single Plant, MP: Multiple Plant. The production rate numbers respond to the manufacturing scales designed on this work. N_{plants} is the chosen number of factories comprising the multi-plant net.

116

117 iii) Distributed Manufacturing (DM). This is also based on the 'artisanal' method and it seeks
 118 production rates to compete with the industrial process. It consists of a given number of small
 119 facilities/kitchens spread around a community, city or region. The required number of facilities
 120 and workers varies according to product throughput.

121 iv) Centralized manufacturing: Single and Multiple Plant Production (SP, MP). The fourth
 122 scenario corresponds to a big industrial plant –or a number– designed to satisfy product
 123 demand.

124

125 3. Model description

126 The model describes the manufacture of dry cereal porridge based on both industrial and
 127 artisanal manufacturing flowsheets. This allows the scale-down and comparison of the
 128 different scenarios studied at a range of production rates (from 0.5 kg/h up to 6000 kg/h). The
 129 whole set of equations includes mass and energy balances - used to design the process unit
 130 operations (i.e. drying) and evaluate energy demand - economic analysis and carbon footprint
 131 estimation. The viability of each production scenario is assessed using the calculated profits

132 and environmental impacts obtained as model outcomes. Overall, the model consists of 40
133 decision variables, 800 parameters, 2500 equations and has been implemented on Matlab®.

134

135 3.1. Model assumptions.

136 3.1.1. *General assumptions*

137 • The water content of the cereal flour, milk powder, sugar and malt extract considered in
138 the moisture mass balances is 12.0% (The Quaker Oats Company, 1984), 2.5% (Reh
139 et al., 2004), 1.75% (Bitjoka et al., 2007), and 2.0% (Lancaster, 1923) respectively.

140 • The waste for mixing (dry and wet), gelatinization, milling and drying, is taken a value of
141 1% of the unit inflow.

142 • Greenhouse gas emission (GHG) are estimated from calculated energy demand using
143 the corresponding energy conversion factors (Government of the United Kingdom,
144 2017c). These factors estimate the emissions, i.e. environmental impact, associated to
145 different activities such as burning fuels and electricity consumption (see Table S.12 in
146 the Supplementary material for values).

147 • The selling format for is a baby food pouch of 0.2 kg.

148

149 3.1.2. *Industrial production method assumptions*

150 • The time for plant/s annual operation is 16 hours/day for 48 weeks, 5 days a week (2
151 shifts) (Maroulis and Saravacos, 2008), closed for 4 weeks for maintenance.

152 • Equipment size depends on plant throughput. Mass balances provide information of the
153 capacity that each unit must have.

154 • Mills, blenders, stirred tank and storage units are oversized using security factors
155 (Walas, 1990). The chosen unit is the one with the next-higher volume found on the

156 corresponding industrial catalogue: mills (Stedman, 2017), double cone mixer (Tapasya
157 Engineerign Works, 2017) and ribbon blender (Paul O. Abbe, 2017).

158 • Different efficiencies for the boilers and burners are assumed during the operation,
159 depending on the fuel: 72.5% for natural gas, 76.0% of heavy fuel oil and diesel, 80.0%
160 for coal and 65.0 % for biomass (CIBO, 2003).

161 • The condensed steam obtained from the drying stage is used to heat the slurry in the
162 gelatinization stage, giving some heat integration.

163

164 3.1.3. *Artisanal production assumptions*

165 • Artisan methods (i.e. HM, FI and DM) are based on batch processes, with only the drying
166 stage overlapping.

167 • Milling, mixing and gelatinization times are assumed the same as in Industrial
168 Production. Packing time for HM is considered as 30s per sealed pouch –see Table 1.

169 • The working day for single worker scenarios –i.e. HM and FI– is 8h per day (1 shift). DM
170 is assumed to comprise two shifts per day, reaching 16 h/day of operation. The three
171 artisan scales operate for 48 weeks, 5 days a week, as for Industrial Production.

172 • For HM, only one piece of each equipment is available. The batch size is therefore the
173 volume of one food processor, i.e. $1.5 \times 10^{-3} \text{ m}^3$. Solution of the corresponding schedule
174 problem leads to a single batch size of 25 pouches of 0.2 kg, four being the maximum
175 number of batches per day.

176 • FI and DM facilities provide more than one piece of equipment. The initial batch volume
177 for both scenarios is $3.0 \times 10^{-3} \text{ m}^3$. A maximum of three batches of 51 pouches can be
178 produced in a working day by a single worker for FI. DM throughput per facility depends
179 on the number of ovens considered.

- 180 • For DM, the number of ovens per facility that allows the cheapest operating cost is
 181 computed. The upper bound is set as four ovens per facility. No limit on the number of
 182 other units is considered. One worker for every two ovens is assumed. Two kind of oven
 183 are studied: electric and gas.
- 184 • No labor costs have been associated to HM and FI scenarios. As 'gig-economy' based
 185 scenarios, the workers are the beneficiaries of the economic activity keeping a
 186 percentage of the sales (Stanford, 2017).

187

188 Table 1: Unit operations, operating conditions and equipment used for industrial and artisanal
 189 dry food manufacturing processes.

Unit Operation	Main Conditions	Equipment	
		Industrial Production (Fig. 2)	Artisanal Production (Fig. 3)
Milling	5 min ^[16]	Cage mill	Food processor
Dry mixing (1)	15 min ^[17] Sterile atmosphere (industrial)	Double Cone Blender	Stand Mixer
Wet mixing	Moisture content up to 80 w% ^[18]	Ribbon Blender	
Gelatinisation	T = 88 °C ^[19,20] 20 min	Jacketed Stirred Tank	Cooking Pot
Drying	Moisture content: up to 6 w%	Double Drum Dryer	Domestic Oven
Cooling	Atmospheric Temperature	Belt Conveyor with Conditioned Air	Natural Cooling
Dry mixing (2)	15 min ^[39] Sterile atmosphere (industrial)	Double Cone Blender	Stand Mixer
Packing	30s/pouch	Automatic Packing Machine	Vacuum Sealer

190

- 191 • HM has no building cost associated as the activity is developed on the worker's kitchen.
 192 In the FI case, a monthly payment (kitchen fee) has been added to the operating cost.
 193 For DM, the kitchens are rented, assuming a surface of 20m² per unit.
- 194 • HM uses existing personal kitchen instrumentation. However, depreciation of this capital
 195 is considered for future replacement of equipment due to use. For FI, no fixed capital is
 196 assumed as both equipment and building are rented.
- 197 • Initial investments, i.e. working capital, are considered equal to the operating cost of one
 198 week, the same as inventory cost.

199

200 3.2. Mass and energy balances

201 Mass balances give the amount of each cereal to be milled and the water to be added. No
 202 accumulation is assumed in the process units. The amount of materials that enter the
 203 equipment is processed during the set residence time –see Table 1. When treatment has
 204 finished, the total mass is sent to the next stage. Equation (1) and (2) correspond to the global
 205 and component *i* mass balances, respectively, for *J* inlet and *K* outlet streams.

$$\sum_{In} \dot{M}_J - \sum_{Out} \dot{M}_K = \dot{M}_{Accum} + \dot{M}_{Waste} \quad (1)$$

206

$$\sum_{In} \dot{M}_J * x_i - \sum_{Out} \dot{M}_K * x_i = \dot{M}_{Accum} * x_i + \dot{M}_{Waste} * x_i \quad (2)$$

207 where \dot{M}_J, \dot{M}_K are mass fluxes (kg/s) and x_i (w/w) are mass fractions.

208 As thermal processes are involved in manufacturing (i.e. gelatinization, cooling, drying and
 209 steam production), energy balances are performed to evaluate heat needs. The first two
 210 involve sensible heat alone, while the last two involve both sensible and latent heat transfer
 211 (Equation 4).

$$Cp_{prod} = \sum_i^n x_i * Cp_i \quad (3)$$

212

$$\dot{Q}_{tot} = \dot{Q}_{sensible} + \dot{Q}_{latent} = \dot{M} * C_{p_j} * \Delta T + \dot{M} * \Delta H^{evap} \quad (4)$$

213 where $C_{p_{prod}}, C_{p_i}$ (J/kgK) are specific heats of the product and single components
214 respectively, ΔT (K) is the product temperature change through the process and ΔH is a
215 general phase change enthalpy to represent heats of vaporization (for drying) or gelatinization
216 (10 kJ/kg) (The Quaker Oats Company, 1984). The total energy required by each thermal
217 process is calculated as the sum of the corresponding sensible and latent heats, as defined
218 by Equation (4).

219

220 3.3. Drying operations

221 The drying step demands around 86 % of the heat supplied for the entire manufacture
222 process. Special attention is needed to model dehydration at all scales.

223 For Industrial manufacture, the operation of a double-drum dryer was described
224 considering heat transfer by conduction with a resistance model to define the overall heat
225 transfer coefficient (Almena et al., 2018). This model was used in a design problem that
226 considers the drum dimensions (diameter, length and gap distance between them) and
227 product formulation (i.e. water content of the wet slurry, density of the wet slurry) as input
228 variables. The process variables that minimize the energy consumption while ensuring a target
229 final moisture content (6% w/w) were found. Values for the steam temperature and rotational
230 speed of the drums were then fed into energy and mass balances. Details for the drum dryer
231 design are given in the Supplementary Material (Table S.4 and Table S.5).

232 The operation of the convective oven was described on a similar way, although heat
233 transfer has been defined considering both convection and radiation. A drying rate of 5.24 kg
234 of water/h has been estimated for the domestic oven. Details on how this value has been
235 obtained are presented in the Supplementary Material (Table S.4).

236

237 3.4. Cost estimation

238 Economic evaluation at plant scale was carried out following the procedure found in Almena
239 and Martin (2016), with total annual production cost and total capital estimated using the
240 *Individual Factors* method (Peters and Timmerhaus, 2003; Silla, 2003; Sinnott and Towler,
241 2013). The factors used are shown in Table S.7 and Table S.8 in the Supplementary Material.

242

243 3.4.1 Total capital

244 Total capital was defined as the total investment required for construction and start-up, i.e.
245 cost of the equipment, piping and instrumentation, building and land charges, project fees,
246 start-up, contingency and working capital. The equipment purchase and installation is
247 estimated using correlations from Matches' Process Equipment Cost Estimates database
248 (Matches, 2014), and installation factors (see Table S.1 and Table S.9 in the Supplementary
249 Material). Building and land surfaces are estimated assuming an area of three and four times
250 the area occupied by the equipment, thus including safety distances (Mecklenburgh, 1973).
251 Building and land areas are then costed using average cost in the UK (Government of United
252 Kingdom, 2015; Jewson, 2017) –1029.3 \$/m² and 482,000 £/hectare (66.2 \$/m²). For DM fixed
253 capital comprises the refurbishment of kitchens, cost of instrumentation, purchase of auxiliary
254 materials (utilities factor) and one-year rent as deposit.

255

256 3.4.2 Production cost

257 The total production (or operating) cost is defined as the annual expense related to
258 manufacture. It comprises: raw materials and packages, electricity and fuel, direct and indirect
259 labor, utilities, supplies, maintenance, laboratory cost, depreciation of the equipment, property
260 taxes, insurance and management cost. Prices of the raw materials are listed in Table S.10
261 (industrial method) and Table S.11 (artisanal method) in the Supplementary Material. Energy

262 prices are also in the Supplementary Material (see Table S.12). Labor cost, equipment
263 depreciation and management cost are not computed using individual factors.

264

265 3.4.3 *Labor cost and equipment depreciation*

266 An organization chart is developed showing direct and indirect labor for the plant (see
267 Figure S.1 in the Supplementary Material) and DM (see Figure S.2). The cost is the average
268 salary for each different job in the year 2017 (Payscale, 2017). Depreciation is computed
269 assuming straight-line depreciation (Peters and Timmerhaus, 2003), while the rest of the cost
270 items are estimated using the corresponding factor.

271

272 3.4.4 *Management cost*

273 For HM and FI scenarios, examples of the ‘gig-economy’, management is carried out by the
274 company. This follows the approach of Uber[®] and Airbnb[®] in other sectors, costing a fee of
275 20% (Huet, 2015) over the baby cereal porridge sales revenue. The seller is the main
276 responsible for the quality and hygiene of the product, as must follow the food hygiene
277 regulations set by the government. The company in charge of management (e.g. the
278 analogous to Uber) would also seek for the highest quality of the products to protect the brand,
279 so part of the management fee would be used to meet the food quality and safety standards,
280 and developing new techniques and products. Management cost at DM and SP/MP scales
281 comprises different items (see Table S.7). Individual factors used for the Industrial Process are
282 shown. For DM, management is necessary to ensuring proper performance of the scattered
283 manufacturing facilities. As a first approach, marketing cost includes the overhead costs of the
284 product (Peters and Timmerhaus, 2003). Quality and hygiene must be controlled and increase
285 the management cost. Due to the degree of complexity, two levels of management have been
286 considered. The lower bound considers each facility as a local business where the owner must
287 fulfil all the standards set by the UK Food Standards Agency (FSA) –i.e. a franchise model–
288 with the supervision of the company that provides the brand. For the upper bound, a single

289 company manages the whole business. Specialized technicians are constantly in charge of
290 the food security and quality with two visits per month at each facility. Facilities are divided up
291 to areas with an assumed maximum of 10 branches, with managers in charge of each area
292 (see Figure S.2).

293

294 3.5 Net profit calculation

295 The Net Profit per facility (Π_{bf}^{fac}) is calculated from Equation 5. Value Added Tax
296 ($\%VAT_{bf}$) for baby food is set at the 0% in the UK (Government of United Kingdom, 2017a)
297 and the Corporation Tax Reduction ($\%Tax_{corp.}$) is the 19 % of the Gross Profit (Government
298 of United Kingdom, 2017b).

$$\Pi_{bf}^{fac} = \left(1 - \frac{\%Tax_{corp.}}{100}\right) \left[\left(1 - \frac{\%VAT_{bf}}{100}\right) (q_{bf} p_{bf} - C_{bf}) \right] \times \left(\frac{1}{N_{facilities}} \right) \quad (5)$$

299 Where q_{bf} is the annual quantity of product sold, p_{bf} is the price of the product, C_{bf} is the
300 annual operating cost and $N_{facilities}$ is the number of facilities.

301 For decentralized scenarios, it is assumed that the whole sales revenue is equally divided
302 among all the facilities. Π_{bf}^{fac} for HM and FI –‘gig-economy’ scenarios– represent the income
303 per independent contractor, while for DM the revenue goes to the owner of one branch
304 comprising the net of facilities that develops the food production.

305

306 4. Results and Discussion

307 The designed tool generates data for different scenarios. For each, it provides cost
308 estimation, design of equipment, number of facilities and labor requires, energy demand and
309 GHG emissions associated, etc. Different manufacturing scales are compared by finding
310 operating cost per kilogram of product manufactured over the full range of scales. The

311 profitability of one scale over the others is therefore set by the cost per unit, assuming the
312 selling price is constant.

313 The data is analyzed to find points that imply trend variations, such as the highest change
314 on slope (HCS) or the plateau reaching point (PR). We consider the plateau is reached when
315 the value of the derivative remains below 10^{-4} . On this basis, the effect of scale on these
316 characteristic points is going to be studied.

317 The model was used to simulate throughputs from 0.5 kg/h to 6000 kg/h and the different
318 scales of production were compared. In addition, we have employed the model to assess a
319 case analogous to the UK, analyzing how decentralized methods for the production of dry
320 cereal porridge would supply the entire UK demand.

321

322 4.1. Effect of the production scale on the operating cost

323 The production rate is defined as a variable. Figure 4 shows unit costs for each production
324 scenario as a function of the production rate (kg/h). Results show that the steepest slope
325 appears when the throughput grows from very low values. At some point, the slope become
326 less pronounced and keeps flattening until a plateau is reached. The same performance is
327 observed for all manufacturing scales. Artisan manufacturing scales show discontinuities
328 related to the addition of a new facility when the maximum capacity of the net is reached. Such
329 steps also exist for industrial manufacturing, but they are less prominent, so the curves look
330 smoother.

331 HM provides feasible and profitable manufacturing scenarios at very low production rates.
332 The FI case is displaced to the right and production is slightly more expensive. Both
333 management cases for DM are also presented in Figure 4.

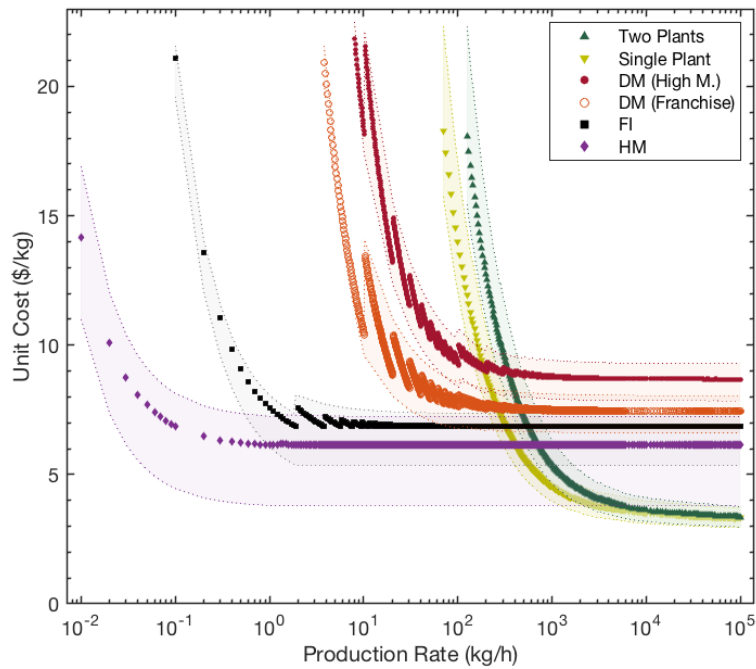


Figure 4: Variation of the unit cost with throughput for different production scales. Unit costs above 10 \$/kg (assuming UK market prices) incur in economic loss and thus result in non-profitable production scenarios. According to this, SP is not profitable above 200 kg/h; DM range of operation is profitable below 60 kg/h (high management) and 20 kg/h (franchise - low management); HM and FI result in unit costs below the 10\$/kg profitability bound even at very low production rates.

334

335 Results shown correspond to the cheapest solution considering 4 ovens per facility. As
 336 expected, the SP scenario gave lower unit costs but reached a plateau at significant higher
 337 capacities. For the multi-plant scenario, when the production is halved into two plants of the
 338 same capacity operating cost increases when compared to the one plant production – showing
 339 economies of scale. The data analysis from Figure 4 is addressed in Section 4.2.

340 *4.1.1 Breakdown of the unit cost*

341 The operating cost per unit has been broken down and analyzed. Costs can be classified
 342 as variable and fixed. Variable cost items –e.g. raw materials and package cost– increase with
 343 throughput. However, variable cost per unit of product is constant. Fixed cost items are
 344 independent of production rate and so fixed cost per unit depends on the production rate

345 studied. The overall fixed cost is different for each production scale, increasing with the size
346 of the manufacturing facilities. HM has depreciation of instrumentation as a fixed cost which
347 becomes very expensive at extremely low production rates. The unit cost rapidly decreases
348 as more product is produced. For FI, fixed cost is related to the food incubator fee and the
349 share on the total unit cost is higher than HM. Therefore, this approach requires more product
350 units to spread the fixed cost, i.e. the feasible region starts at higher production rates. DM
351 involves higher fixed cost than the two previous manufacturing scales. Each facility requires
352 labor, rent, instrumentation and management cost; as a result, DM requires higher demand
353 scenarios (ca. 30 kg/h assuming low management) for profitability. The solution for the three
354 artisan manufacturing scenarios shows a maximum when an additional facility is required, and
355 then the effect of that expense is lowered until the maximum capacity is reached. The
356 amplitude is greater as the scale of manufacturing increases, when it requires a higher
357 injection of fixed cost. However, the amplitude of the step decreases with increasing
358 throughput values, as shown in Figure 4. This is also an effect of spreading the fixed cost over
359 a higher number of units produced.

360 Industrial manufacture gives cheaper variable cost (raw material and package prices are
361 lower) so these scales reach a plateau at lower unit cost values. Here the fixed cost share is
362 negligible compared to the variable cost. However, as the overall value of fixed costs is greater
363 than for artisan manufacture, SP and MP need to operate at large production rates to be
364 profitable. Both SP and MP present similar trends. However, the more expensive fixed cost
365 assigned to MP shift the curves to the right, while variable costs contribution remains the
366 same.

367

368 *4.1.2 Unit cost sensitivity analysis*

369 Unit operating costs depend on a number of factors characterized by uncertainty, for example
370 price fluctuations, capital cost or marketing cost. The uncertainty on the estimation of the

371 capital cost is studied by increasing capital up to 40% as upper bound and a decrease of to
372 20% as lower bound. This asymmetric spread towards the positive error is considered as
373 uncertainty is frequently caused by omission of items in design (Peters and Timmerhaus,
374 2003). Marketing costs estimation factor varies depending on the ratio $\left(\frac{\text{quantity sold}}{N^{\circ} \text{ customers}}\right)$ for the
375 product sold, increasing when this ratio is very small. Here, it is considered as 15% of
376 production cost, within the uncertainty range: 22% (upper bound) and 5% (lower bound)
377 (Peters and Timmerhaus, 2003). Both effects constitute boundaries for a sensitivity analysis
378 for industrial manufacturing. For artisan manufacturing scales, the same uncertainty factors
379 for capital and management cost are taken. Fluctuation on the raw material price is also
380 assumed. Thus, an increase of 15% over the standard price is taken as upper bound
381 (Nakamura, 2008), while the lower bound would correspond to wholesale price, i.e. a discount
382 of 21% (average gross profit margin for supermarkets) over the standard retail price of raw
383 materials (Chidmi and Murova, 2011; Jindal et al., 2018).

384 Table 2 shows the crossover points for HM, FI and DM plots with the SP & MP curves
385 displayed in Figure 4, including uncertainty bounds. Those points suggest where the artisan
386 manufacturing scales become more cost-effective than industrial scenarios:

- 387 • HM and FI scenarios are always cheaper than SP for <215 kg/h of production (around
388 52% of UK demand) in the worst-case scenario -i.e. upper bound for artisan scales and
389 lower bound for Single Plant. Uncertainties aside, HM is cheapest for throughputs below
390 400 kg/h.
- 391 • The DM with low management cost (franchise) is more cost effective than the SP
392 scenario for production rates below 261 kg/h (in the range 174 – 495 kg/h), while when
393 considering a high management cost the cut-off point is reduced down to 194 kg/h,
394 between 125 and 326 kg/h. The importance of management cost in DM is clear.

395

396

Table 2: Crossover points from Figure 4 for each manufacturing scale, including uncertainties: lower bound (lb) and higher bound (hb). A pair of values is associated to each intersection. The upper value corresponds to the x-axis coordinate (*throughput – kg/h*), while the lower is the y-axis coordinate (*unit cost – \$/kg*).

Throughput (kg/h) Unit Cost (\$/kg)	SP (lb)	Single Plant	SP (hb)	MP (lb)	Multi-Plant (Two Plants)	MP (hb)
HM (lb)	1,235 3.79	-	> 6,000 3.79	2,160 3.79	-	> 6,000 3.79
Home Manufacturing	-	407 6.13	-	-	723 6.13	-
HM (hb)	220 7.24	-	409 7.24	383 7.24	-	739 7.24
FI (lb)	400 5.36	-	924 5.36	711 5.36	-	1685 5.36
Food Incubator	-	321 6.86	-	-	566 6.86	-
FI (hb)	214 7.36	-	394 7.36	375 7.36	-	719 7.36
DM low M. (lb)	252 6.71	-	495 6.65	448 6.67	-	898 6.63
Distributed Manufacturing (low Manag.)	-	261 7.59	-	-	466 7.52	-
DM low M. (hb)	174 8.36	-	316 8.25	306 8.26	-	581 8.14
DM high M. (lb)	175 8.24	-	326 8.13	316 8.15	-	612 7.94
Distributed Manufacturing (high Manag.)	-	194 8.99	-	-	342 8.99	-
DM high M. (hb)	125 10.30	-	225 9.86	234 9.81	-	428 9.59
SP (lb)	-	-	-	> 6,000 < 3.19	-	No cross
Single Plant	-	-	-	-	> 6,000 < 3.60	-
SP (hb)	-	-	-	265 9.00	-	> 6,000 < 4.10

397

398

399

- For MP (2 plants), crossover points with artisan scenarios are obtained at higher production rates than SP. It can be considered as an alternative to SP for throughput values above 265 kg/h, when the uncertainties start to overlap.

400

401

402

403 4.2. Data trend analysis on unit cost curves for each manufacturing scale.

404 The methodology described in Section 4 is applied to the data of Figure 4. For each
405 manufacturing scale curve, HCS and PR points are computed. Figure 5 compares one
406 example of artisan manufacture (i.e. DM at low management) to one of industrial
407 manufacturing (SP).

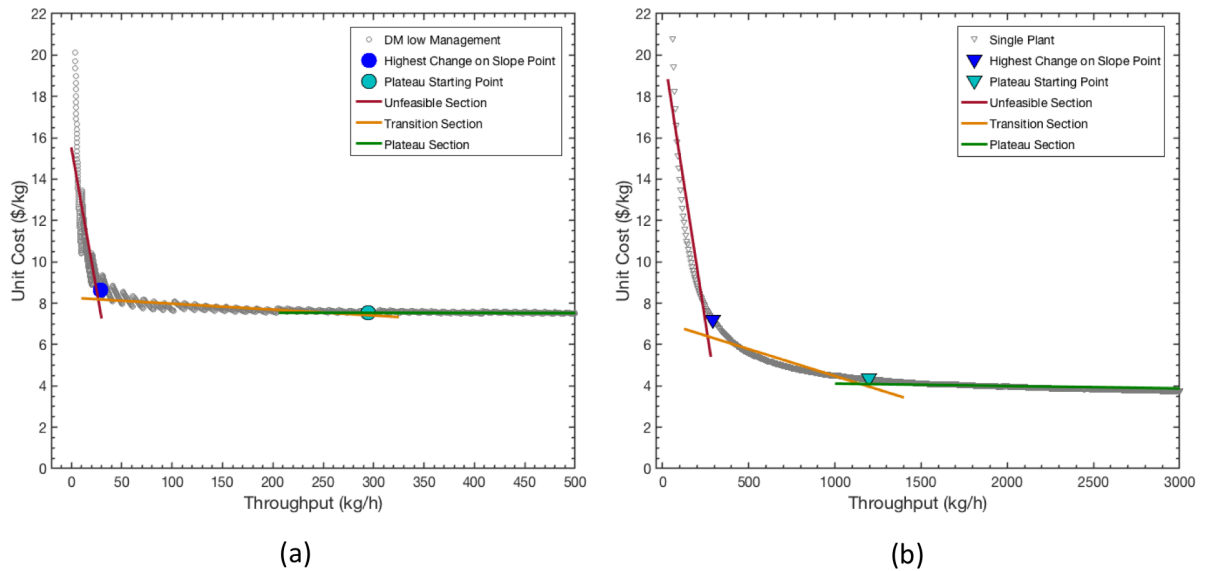


Figure 5: Example of how the different operation regions for a manufacturing scale are identified. Graphs show (a) DM low Management (b) Single Plant scenarios. Dark blue marks (dots for (a) and triangles for (b)) represent the biggest change on slope, while light blue ones indicate the plateau starting point. This divides each graph in three regions: 'Unfeasible' (red), 'Transition' (orange) and Plateau ('green'). The lines represent the linear fit of the points belonging to each section.

408

409 HCS and the PR points divide the data in three recognizable regions. The left section
410 comprises the points with the highest slope, where a small increase in the production leads to
411 a significant cost reduction. The scenario is non-feasible, as any profit-seeking company
412 would increase the investment for a greater production if it is cost effective. When the first
413 characteristic point is reached, achieving cost reduction requires a higher increase on
414 productivity, i.e. an important capital injection. Scenario within the transition section, between
415 HCS and PR, could be feasible if it is profitable. The right region represents the plateau, where
416 there is no cost reduction from increasing the production rate. Profits grow with the number of

417 product units sold, so companies with no limit on investment and enough market share will
 418 invest in bigger production scenarios.

419 The values of HCS and PR points and the linear fitting for unfeasible, transition and plateau
 420 regions for all manufacturing scales are compiled in Table 3. HCS points, representing the
 421 end of the unfeasible region, are reached at a higher throughput when increasing the facility
 422 scale (i.e. max capacity of the manufacturing facility).

423

424 Table 3: High change on slope (HCS) and plateau reaching (PR) points for each
 425 manufacturing scale, for which x-axis coordinate (throughput – kg/h) and y-axis coordinate
 426 (unit cost – \$/kg) are given. This table also shows the linear fitting for each operating region
 427 the manufacturing scale is divided in, as the examples shown in Figure 5.

428

	Unfeasible section		HCS	Transition section		PR	Plateau section	
	<i>slope</i>	<i>intercept</i>	(kg/h) (\$/kg)	<i>slope</i>	<i>intercept</i>	(kg/h) (\$/kg)	<i>slope</i>	<i>intercept</i>
HM	-118.85	13.53	0.06 7.41	-0.062	6.44	7 6.14	-2.24 $\times 10^{-7}$	6.13
FI	-27.75	21.25	0.5 9.07	-0.011	7.14	32 6.87	-2.63 $\times 10^{-6}$	6.86
DM (low M.)	-0.28	15.53	28.5 8.65	-0.003	8.26	291 7.57	-4.80 $\times 10^{-5}$	7.55
DM (high M.)	-0.21	19.29	49.2 10.41	-0.002	9.67	557 8.8	-6.96 $\times 10^{-5}$	8.86
SP	-0.05	20.45	290.0 7.21	-0.003	7.08	1195 4.35	-9.17 $\times 10^{-5}$	4.23
2P	-0.08	30.62	295.0 9.88	-0.003	8.87	1520 4.70	-9.77 $\times 10^{-5}$	4.70

429

430

431 HM and FI reached this point for one operating facility, while DM does it for the third and
 432 fifth facility depending on the management. For industrial production in single plant and two
 433 plants, they are reached at similar overall production rates (≈ 300 kg/h) but at a greater

434 operating cost for the latter. Both HM and SP reach transition region at similar cost values
435 around 7.3 \$/kg, but at a throughput difference of four orders of magnitude (0.06 and 290 kg/h
436 respectively). PR points are reached at higher production rates than HCS, but showing a
437 similar behavior. Although the fall in cost for industrial manufacturing scenarios when the
438 plateau appears is higher (4.35 for SP and 4.70 for 2P), it is reached at a very high production
439 rate, nearly three and four times the entire demand of dry baby food in the UK for SP and 2P
440 respectively. On the other hand, artisan manufacturing scenarios achieve all their cost
441 effectivity potential at lower production rates. The cost and throughput values when a plateau
442 is reached increase with the size of the facility. HM does it at 7 kg/h (7 operating facilities) at
443 a cost slightly above 6.1 \$/kg and FI when 17 facilities are working with a cost under 6.7 kg/h.

444 For DM, PR points appear at greater throughput and unit cost values especially when the
445 management cost is high. DM at low management reaches the cost floor (7.55 \$/kg) when 29
446 facilities operate, while high management requires 55 facilities at a most expensive outcome
447 (8.86 \$/kg).

448 The last conclusion we can take from this methodology is the length of the transition region
449 for each manufacturing scale. Industrial manufacturing (see Figure 5) shows the longest
450 section, showing the effect of the economy of scale.

451

452 4.3. Effect of manufacturing scale on total capital

453 Total Capital is used to compare the four production scales addressed here. This value
454 represents the ease of market entry for a company. The investment needed for each
455 manufacturing scale is depicted in Figure 6(a). The highest values correspond to Industrial
456 Manufacturing. Substantial investment is required for construction and start-up of an industrial
457 plant, and this increase when scaling from a single plant to two, with an addition of around 7
458 MM\$. The steps result from bigger instrumentation requirements, when the maximum capacity
459 any of the previous equipment is reached.

460

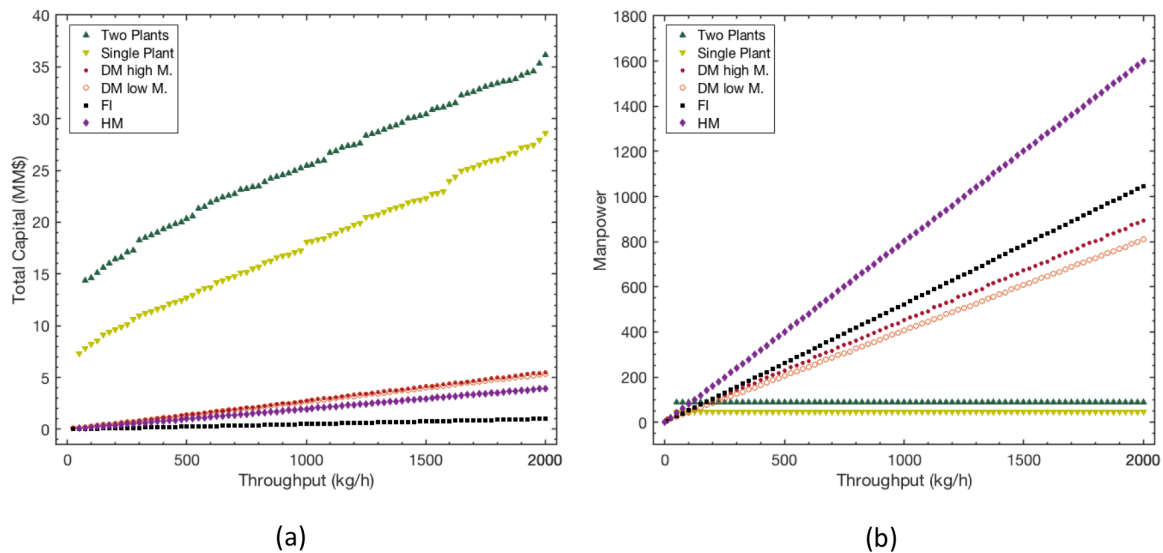


Figure 6: (a) Total capital and (b) Manpower required for each production scale at different final product's production rates. Industrial manufacture requires a much larger investment than artisanal production scales, as depicted in (a). Furthermore, the greater number of facilities for small scales requires more labour force, as shown in (b).

461

462 On the other hand, artisan manufacturing scenarios require far less investment –around
 463 15% of SP capital– as these decentralized scenarios use rented facilities, and kitchenware is
 464 cheaper than industrial equipment. The trend is linear, directly related to the number of
 465 facilities. It can be observed that capital is not very sensitive to management cost, resulting in
 466 the overlap of the two DM trend lines. HM has capital values close to DM ones due to the high
 467 number of facilities– required to produce the same throughput –around 10 to 1. It should be
 468 noticed that for HM capital is not required for starting the business as assets are assumed to
 469 already exist. However, the depreciation of equipment and the value of the assets are
 470 computed as the participants will need to replace them when the lifespan is reached. A
 471 different assumption is considered for FI, where assets are rented to the owner, being this fee
 472 included on the annual operating cost.

473 Figure 6(b) show the manpower needed at each production rate. Industrial manufacturing
 474 labor remains constant, as plants require the same personnel. If two plants are considered,
 475 the manpower increases, although not doubling as the senior management is shared. For

476 artisanal manufacturing scenarios, the lowest the scale the highest the manpower required.
477 HM and FI comprise one worker per facility and has the steepest slopes of Figure 6(b).
478 However, being representative of 'gig-economy', labor does not involve any cost as they are
479 the beneficiaries of the economic activity. DM manpower is assumed to be salaried
480 employees, representing the most significant contribution to unit cost for this manufacturing
481 scale. Labor cost becomes even greater those scenarios that include more management
482 personnel.

483 484 4.4. Case study: the UK dry baby food demand scenario.

485 Here, the tool is applied to the demand of dry baby food over the scale of the UK. The
486 whole demand (both dry and wet) of baby food for the year 2015 was 32,000 t (Intel, 2016),
487 while the market share of dry baby food in the UK is estimated as a 5% of the total production
488 (Minister of Agriculture and Agri-food Canada, 2016). Therefore, a production rate of 418 kg/h
489 is enough to supply the UK dry baby food demand.

490 The seven different scenarios, namely HM, FI, DM, Single-Plant and Multi-plant (splitting
491 from 2 to 4 plants of same capacity) have been assessed and compared. In a UK-based
492 framework, results show that a HM scenario employs 334 cooks, while for FI this is reduced
493 to 219. For DM, 41 facilities spread all over the country with 194 workers –171 for low
494 management– are needed. Results of the mass and energy balance, together with
495 specifications of the equipment are listed in Table S.13 and Table S.14 of the Supplementary
496 Material respectively.

497

498 *4.4.1 Total capital*

499 Total capital corresponding to each UK-based scenario is presented in Figure 7(a). Results
500 show the effect of initial investments (e.g. machinery, land or buildings), as artisanal
501 manufacturing scenarios exhibit much lower values than the industrial scenarios. For example,

502 the DM scenario requires as initial investment the 9.6% of SP capital. The increase in capital
503 required to go from single plant (12.1 MM\$) to two plants is 7.4 MM\$ (61.4%). When scaling
504 from two plants to three, the rise is smaller –6.4 MM\$ (34%)– and increases again when
505 adding an additional plant –7.1 MM\$ (26%).

506
507 *4.4.2 Unit operating cost*

508 The production cost for each scale (1 kg of final product as basis) is presented in Figure
509 7(b). The average selling price of dry baby cereal porridge –found in UK supermarkets (Tesco,
510 2016)– is ca. 10 \$/kg. The production cost must be below this to achieve profitability. The
511 lowest scale production scenarios, i.e. HM and FI, involve the lowest unit cost. The impact of
512 the labor cost paid and the high management cost as a result of moving from ‘gig-economy’
513 to Distributed Manufacturing, increases the production cost. Results thus show HM (6.13 \$/kg)
514 and FI (6.86 \$/kg) as scenarios with the lowest production cost using artisanal manufacture.
515 DM franchise scenario production cost (7.52 \$/kg) is 22.7% greater than HM one, and 45.5%
516 greater when high management is assumed (8.92 \$/kg). For SP, the annual operating cost is
517 6.06 \$/kg, comprising the cheapest scenario and followed very close by HM (1.2% higher).
518 The maximum unit cost, however, corresponds to the Multiple-Plant cases when there are
519 more than two plants operating. Overall, the high investment required to build a processing
520 plant, measured in terms of financial cost and depreciation, increases cost at low throughput
521 when new plants are added. However, using two plants to supply the UK demand appears
522 cheaper than the DM scenario for high management conditions.

523

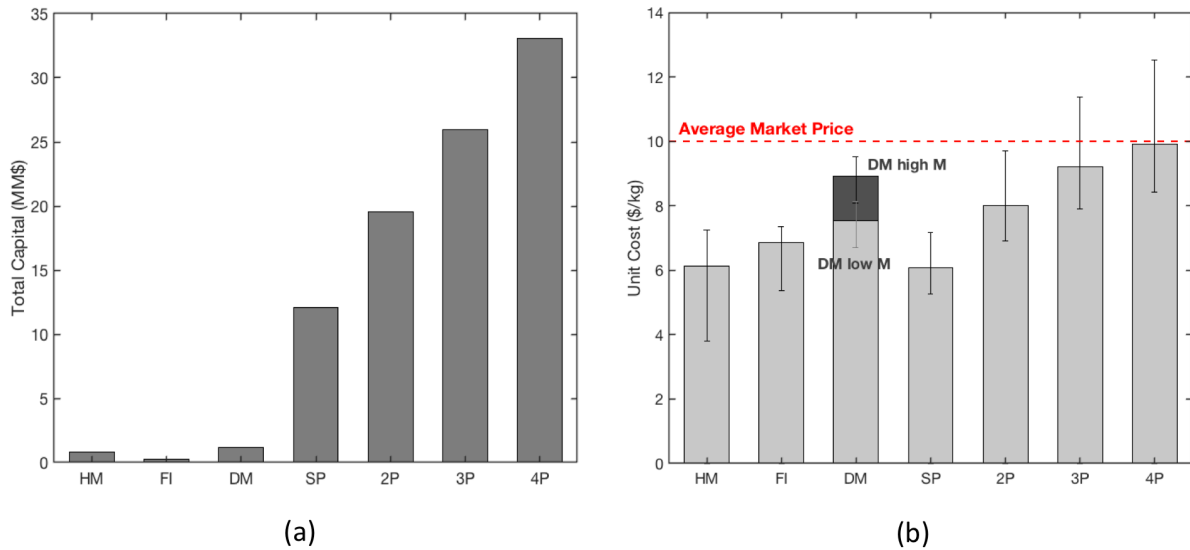


Figure 7: Total capital (a) and unit operating cost (b) for HM, FI, DM, SP and MP production scenarios under UK dry baby food demand (418 kg/h). In (b) DM has two unit operating cost values for high management (dark bar section) and franchise (light bar section). Error bars show the uncertainties for each scale. As shown in (a) DM requires significant lower capital (approx. 10% less) than SP production scenarios. Sharing economy scenarios need even lower total capitals (<1MM\$), while increasing the number of plants rises total capital almost linearly. Unit costs for each scale analysed are consistently below average market price (red dashed line in (b)), with HM, FI and DM (franchise) close to SP production operating costs.

524

525 4.4.3 Net profit

526 The selling price is kept constant for all the manufacturing scenarios. Nationwide profit –
 527 i.e. whole net of facilities profit– and Π_{bf}^{fac} values are provided. The nationwide annual tax-
 528 free profit is 4.97 MM\$ (14,850 \$/yr.kitchen) for HM and 4.03 MM\$ (18,400 \$/yr.kitchen) for
 529 FI. Although FI has a higher unit cost, the higher production per facility allows greater profit
 530 per contractor. DM profitability strongly varies with management cost assumptions, being 1.39
 531 MM\$ (33,000 \$/yr.facility) and 3.18 MM\$ (76,830 \$/yr.facility) for high and low management
 532 case respectively. Single-Plant manufacture gives the highest profit of 5.06 MM\$/year, while
 533 for two plants it decreases to 2.57 MM\$/year (1.28 MM\$/year.plant).

534

535 *4.4.4 Energy demand and carbon footprint at manufacture stage*

536 Table 4 shows the results of energy demand and carbon footprint associated for the UK
537 scenario. Multiple fuels have been considered. For artisanal manufacturing, electric oven and
538 gas oven are assessed. Regarding industrial manufacturing, there is the possibility of using
539 several energy sources for the steam fired boiler. Similar individual numbers have been
540 obtained for all scenarios. However, for the annual energy consumption at each scale the
541 difference is substantial. Natural gas is assumed to be used for all scales in the economic
542 results previously discussed. For artisan manufacture, a domestic gas oven is assumed to
543 have an efficiency of 45% (Ko and Lin, 2003), while electric ovens are more energy effective
544 (60%) (The Carbon Trust, 2015). The double drum dryer is assumed to require 1 kg of steam
545 per 0.71 kg of water evaporated (Ramli and Daud, 2014).

546 The carbon footprint for on each scenario was estimated from calculated energy using the
547 UK Government Greenhouse Gas (GHG) Conversion Factors (Government of the United
548 Kingdom, 2017c). This provides the GHG emissions data that every manufacturer must report
549 to the UK government. The carbon footprint of the industrial process is the lowest, producing
550 0.530 kg CO₂e per kg of product manufactured, as shown in Table 4. An additional plant
551 increases the emissions by 4% as the energy efficiency slightly drops.

552 Among the alternative fuel sources, a boiler fed with biomass (pellets) carries the least
553 carbon footprint, despite being less energy effective. The use of this kind of boiler at industrial
554 scale is still challenging. For the alternative manufacture methods, environmental impact
555 factors related to these scenarios give emissions around 15% higher than industrial ones. HM
556 carries the least emissions within artisanal manufacture with 0.596 kg CO₂e/kg. FI and DM
557 slightly increase the carbon load by 2% and 3%. If electric ovens are used for drying, the
558 energy demand decreases by 40% from natural gas, but the environmental impact rises by
559 33%.

560

561 Table 4: Carbon Footprint of HM, FI, DM, SP and MP (two plants) at the manufacturing stage.
 562 Artisanal production scales show results for both electric and natural gas oven cases.
 563

Manufacturing Scenario	Total Energy kJ/kg	Electricity Consumption kWh/kg	Fuel Consumption kg/h	$C_{Electrici}$	C_{fuel}	C_{Total}
				$kg CO_2e/kg$		
HM						
-electric oven-	7002.0	1.945	–	0.801	–	0.801
-gas oven-	9086.0	0.208	2.316	0.086	0.474	0.560
FI						
-electric oven-	7077.2	1.966	–	0.810	–	0.810
-gas oven-	9120.3	0.263	2.270	0.109	0.464	0.573
DM						
-electric oven-	7059.2	1.961	–	0.808	–	0.808
-gas oven-	9102.3	0.258	2.271	0.106	0.465	0.571
SP						
-natural gas-	8946.0	0.102	$97.8 (m^3/h)$	0.042	0.488	0.530
-fuel oil-	8550.9		88.3		0.648	0.690
-diesel-	8550.9		79.8		0.608	0.650
-coal-	8141.7		142.8		0.737	0.779
-biomass-	9935.9		232.1		0.034	0.076
MP (2P)						
-natural gas-	9117.1	0.149	$97.8 (m^3/h)$	0.062	0.488	0.549
-fuel oil-	8722.0		88.3		0.648	0.709
-diesel-	8722.0		79.8		0.608	0.670
-coal-	8312.8		142.8		0.737	0.799
-biomass-	10107.0		232.1		0.034	0.095

564

565

566 **5. Overview and future food manufacture trends and challenges**

567 One of the issues that centralized manufacturing faces is the search for differentiation of
 568 products. Mass customization, delivering differentiated or personalized products with near

569 mass production efficiency, is the goal for many companies in the current diversified
570 marketplace (Tseng and Hu, 2014). However, mass customization with centralization still
571 creates lengthy supply chains. Distributed Manufacture (DM) systems could solve many of the
572 issues of centralized production. Local variation or mass customization can be created from
573 decentralized and small-scale manufacture. Short Food Supply Chains (SFSC) (Sellitto et al.,
574 2018) and Alternative Food Networks (AFN) (Jarosz, 2008) comprise alternative scenarios
575 that shorten the supply chain and suggest the food industry might adopt a 'good food network'
576 based on decentralization (Sage, 2003) and eco-localism (Curtis, 2003) as a path to
577 environmental, economic and social sustainability. Recent studies also point out that AFN's
578 can contribute to ensure food security (Cerrada-Serra et al., 2018; Moragues-Faus and
579 Carroll, 2018). Although the balance between increased production costs and decreased
580 transport cost in decentralized scenarios needs further study, DM could well be used for
581 emerging SFSC or specialized supply chains, e.g. dry supply chains (where products are
582 distributed/stored in dried/powder form and rehydrated closer to the consumers) or
583 frozen/refrigerated chains (decreasing road mileage, cost and GHG emission of refrigerated
584 vehicles).

585 At the smallest manufacturing scale per facility, a very large number of "production units"
586 (labor and stores) is required to duplicate the output of a plant, which can generate new jobs
587 and stronger social impacts in local communities. However, the concept of the 'gig-economy',
588 understood as "crowdwork" or "work-on demand via app", eliminates boundaries for
589 manpower, enhancing market flexibility, albeit at the cost of economic security for many
590 workers (Dokko et al., 2015). Advances in information and communication technologies (ICT)
591 have allowed the contact of an indefinite number of costumers and workers on a global basis
592 (De Stefano, 2016), and the additional concept of a 'sharing economy' (also called
593 'collaborative consumption'), which involves peer-to-peer based activity of sharing the access
594 to goods coordinated by ICTs (Hamari et al., 2016), has overcome the limitation of capital
595 investment at low production rates. These ideas set the basis for different manufacturing

596 models on food processing, by analogy with other industry sectors, e.g. Uber and Airbnb.
597 Modular manufacturing (Baldea and Edgar, 2017) and additive manufacturing (Femmer et al.,
598 2015) are different up-to-date approaches for seeking a decentralized, scalable and flexible
599 production in other sectors of the industry, consolidating these new trends.

600 Distributed based scenarios will involve unavoidable challenges too. The number of
601 facilities required (here 334 for HM) requires time and organization and some regulatory
602 framework (Srai et al, 2016). Although the smallest scale assessed here, involving peer-to-
603 peer services, has been shown to contribute large economic benefits in other sectors,
604 governments will still need to develop policies to protect consumers and providers. The
605 smaller the manufacture scale, the more difficult maintaining the food safety is (Cottee, 2014).
606 This could be the subject of future research. A minimum standard for product quality could be
607 also compromised, only relying on the market self-regulation by review and rating feedback
608 from customers and suppliers via ICTs apps. Localisation implies a closer relationship
609 between manufacturer and consumer (Albrecht and Smithers, 2018). The sellers should
610 provide a high-quality and safe product, while consumers loyalty would support the producer
611 selling on quality and naturalness despite a potential increase on the prize (Groves, 2008).

612

613 **6. Conclusions**

614 A model-based tool for the design, simulation and cost estimation of manufacturing process
615 at several scales of production has been developed and used to assess the profitability of four
616 different scenarios, from decentralized manufacturing (HM, FI and DM) to centralized
617 manufacturing (SP and MP), in the production of a dried food. Operating regions, namely
618 unfeasible, transition and plateau, have been identified for each manufacturing scale.
619 Crossover points showing the boundaries of operation for decentralized scales to be more
620 profitable than industrial scenarios are also predicted. Results show that total decentralization
621 (HM and FI), can be an alternative to centralization by providing competitive operating cost
622 and increased manpower. The DM scenario represents a competitive alternative to the current

623 centralized production, when its management cost is moderate. The low capital required and
624 the sensible number of facilities comprising the net suggest this could be easier to apply at
625 the UK scale. For energy use and carbon load, artisanal manufacture-based scenarios are not
626 advantageous when compared to the industrial processing. Results revealed that splitting the
627 production into two or more plants does not give any advantage for manufacturing in economic
628 terms.

629 Overall, this work shows the capability and flexibility of the proposed methodology to
630 assess the profitability of different manufacturing scenarios at a wide range of production
631 scales. The method allows the variation of multiple parameters, helping in the complex
632 decision between centralized manufacturing or decentralized manufacturing systems. The
633 results demonstrate how different production scales generate profits; although the
634 assumptions and estimations are all taken from reliable sources, they might hardly fit a real
635 industrial system with a high level of accuracy, the method shows that it is possible to generate
636 models at these different scales. A further study of the entire food supply chain for each
637 scenario would show the economical and energy saving potential of the alternative
638 manufacturing methods assessed.

639

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643

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Centralized and distributed food manufacture: A modelling platform for technological, environmental and economic assessment at different manufacturing scales.

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Unit Cost Correlations.

Table S.1. Correlation for equipment cost estimation (Matches, 2014).

Cage Mill	$C_c(\$_{2014}) = 5,657.1 d^2 + 4,057.1 d - 8,671.4$	S1
Double Cone Mixer	$C_{cm}(\$_{2014}) = 3848.50 V^{0.42}$	S2
Ribbon Blender	$C_{rb}(\$_{2014}) = 2,410.10 V^{0.60}$	S3
Jacketed and Agitated Reactor	$C_r(\$_{2014}) = 2,410.10 V^{0.60}$	S4
Double drum dryer	$C_{dd}(\$_{2014}) = 22,425.73 S^{0.38}$	S5
Conveyor belt & conditioned air	$C_{cb}(\$_{2014}) = 484,950.46 Q_{rem}^{0.73}$	S6
Packing Machine	Price 58,000 \$ (Alibaba.com, 2016) $C_p(\$_{2017}) = N^o_{units} \times Price$	S7
Boiler	Pressure up to 150 psi: $C_b(\$_{2014}) = 11.20 \dot{V} + 213,015$	S8
	Pressure 150 to 600 psi: $C_b(\$_{2014}) = 22.02 \dot{V} + 474,139$	S9
	Pressure 600 to 1500 psi: $C_b(\$_{2014}) = 25.21 \dot{V} + 621,581$	S10
Vertical Vessel –Silos and Intermediate tank–	$C_v(\$_{2014}) = 231.50 W^{0.61}$	S11
Marshall and Swift Cost Index (IM&S)	$IM\&S_{year} = 51.39 year - 101,795$	S12
	$C_{MSCI}(\$_{2016}) = C_{MSCI}(\$_{2014}) \frac{IM\&S_{2016}}{IM\&S_{2014}}$	S13

All the cost obtained using these correlations are given as Free on Board (FOB) incoterm, obtained in dollars for the year 2014. For this reason, a shipping fee must be added as 1.1 factor (Silla, 2003), together with an update of this expense for the current year. The update is made using the Marshall & Swift Equipment Index (Economic Indicators, 2012). This data finished in the year 2012, so an extrapolation is made as a valid approach.

Artisanal Process Equipment.

Table S.2. *Cooking instrumentation features.*

Instrument	Price (\$)	Capacity	Electricity consumption (kW)
Food Processor	195.00	1.5 l	0.9
Saucepan	27.00	5 l	N/A
Induction hob	435.00	4 zones	4.6
Oven	780.00	70 l	3.65 / Nat Gas Fed
Vacuum Sealer	69.00	1 bag/min	0.12

Table S.3. *Features of Double drum dryer (Gouda, 2016) and Domestic oven.*

Model #1			
Drum diameter	0.5 m	Drum length	0.5 m
Min Rotational speed	2.2 rpm	Max Rotational speed	22.0 rpm
Min power consumption	4.0 kW	Max power consumption	7.5 kW
Model #2			
Drum diameter	0.5 m	Drum length	1.0 m
Min Rotational speed	2.2 rpm	Max Rotational speed	22.0 rpm
Min power consumption	5.5 kW	Max power consumption	7.5 kW
Model #3			
Drum diameter	1.0 m	Drum length	1.0 m
Min Rotational speed	1.5 rpm	Max Rotational speed	15.0 rpm
Min power consumption	8.0 kW	Max power consumption	35.0 kW
Model #4			
Drum diameter	1.0 m	Drum length	2.0 m
Min Rotational speed	1.5 rpm	Max Rotational speed	15.0 rpm
Min power consumption	15.0 kW	Max power consumption	35.5 kW
Model #5			
Drum diameter	1.0 m	Drum length	3.0 m
Min Rotational speed	1.5 rpm	Max Rotational speed	15.0 rpm
Min power consumption	22.0 kW	Max power consumption	43.3 kW
Model #6			
Drum diameter	1.5 m	Drum length	3.0 m
Min Rotational speed	1.5 rpm	Max Rotational speed	15.0 rpm
Min power consumption	37.0 kW	Max power consumption	100.0 kW
Model #7			
Drum diameter	1.5 m	Drum length	4.0 m
Min Rotational speed	1.5 rpm	Max Rotational speed	15.0 rpm
Min power consumption	44.0 kW	Max power consumption	100 kW
Domestic Oven			
Capacity	70 l		
Power (electric oven)	5.10 kW		
Tray surface	0.275 m ²		
Heat transfer surface	0.550 m ²		
Global heat transfer coefficient	28.0 W m ⁻² K ⁻¹		

Table S.4. Double drum dryer model.

Energy supply at the drum (kW)	$Q_{drum} = U A \Delta T_{lm}$
Overall heat transfer coefficient ($U [=] W/m^2 \text{ } ^\circ C$)	$\frac{1}{U} = \frac{1}{h_{i0}} + r_{di} \frac{d_0}{d_i} + \frac{1}{\kappa_{drum}} + r_{d0} + \frac{1}{\kappa_{d-s}}$
Mean condensation film coefficient inside horizontal tubes ($W/m^2 \text{ } ^\circ C$) (Sinnott and Towler, 2013)	$h_{i0} = 0.76 k_L \left[\frac{\rho_L (\rho_L - \rho_V) g}{\mu_L \Gamma_h} \right]^{1/3}$
Conduction coefficient for the dryer drum ($\kappa_m [=] W/m \text{ } ^\circ C$; $d_0 [=] m$)	$\kappa_{drum} = \frac{2 \kappa_m}{d_0 \ln (d_0/d_i)}$
Conduction coefficient for the drum ($\kappa_{slurry\ gel} [=] W/m \text{ } ^\circ C$; $\tau_{slurry\ gel} [=] m$)	$\kappa_{d-s} = \frac{\kappa_{slurry\ gel}}{\tau_{slurry\ gel}}$
Internal fouling resistance ($m^2 \text{ } ^\circ C / W$) (Sinnott and Towler, 2013)	$r_{di} = 1/f_{steam} = 1/3250$
External fouling resistance ($m^2 \text{ } ^\circ C / W$) (Sinnott and Towler, 2013)	$r_{d0} = 1/f_{slurry} = 1/5000$
Heat transfer surface (m^2)	$A = (X_{blades}) 2\pi d_0 L$
Logarithmic mean temperature difference ($^\circ C$)	$\Delta T_{lm} = \frac{(T_{steam} - T_{Dry}) - (T_{steam} - T_{Gel})}{\log \left[\frac{(T_{steam} - T_{Dry})}{(T_{steam} - T_{Gel})} \right]}$
Drying rate (kg/s)	$\dot{m}_w^f = (Q_{drum} - Q_{sensible\ gel}) / \Delta H_{vap\ H_2O}$
Final moisture content of slurry (kg water / kg slurry)	$x_w^f = \left[\frac{m_{slurry}^0 x_w^0 - \left(\frac{60}{\omega_{drum} X_{blades}} \right) \dot{m}_w^f}{\rho_{gel} A \tau_{slurry\ gel} - \left(\frac{60}{\omega_{drum} X_{blades}} \right) \dot{m}_w^f} \right]$
Objective function	$J_{DD} = \sqrt{\sum (x_w^f - x_w^{target})^2} + \sqrt{\sum (\dot{m}_w^f - \dot{m}_w^{target})^2} + \left(\frac{1}{1000} \right) \sqrt{\sum (Q_{drum} - Q_{dry})^2}$

Table S.5. Double drum dryer design

Design Variable (x_i)	Lower Bound (lb_i)	Upper bound (ub_i)
T_{steam}	100	300
ω_{drum}	Model # ω_{drum}^{min}	Model # ω_{drum}^{max}

Continuous Variable	Value
Q_{dry}	Energy balance (function of production rate)

Discrete Variable	Value
d_0	Model # feature
L	Model # feature

Double Drum Dryer Design Routine	
Initial guess	multi-shot
Tolerance	10^{-14}
Algorithm	Interior point (Matlab)
Solution	$\min (J_{DD})$

Stopping Criteria	Boundary
Maximum Dry equipment surface	100 m^2
Max Diff Heat supply and needed	$\sqrt{\left(\frac{N_{DDD} * Q_{Drums} - Q_{dry}}{Q_{dry}}\right)^2} < 1$

Design Solution: Double Drum Dryer and Boiler minimum cost
$\min \{(C_{da} + C_b)\}$

Table S.6. Domestic convective oven operation

Constant rate of mass loss model (Carson et al., 2006): Apparent heat transfer coefficient.	$h_a = \frac{-\phi L (T_s)}{T_\infty - T_s}$
Water to evaporate in a batch	$m_w^{evap} = m_{Cereal\ Flour}^{batch} \left(\frac{1}{x_w^o} - \frac{1}{x_w^{target}} \right)$
Heat required	$Q_{dry} = m_w^{evap} [\Delta H^{evap} + C_{p_w} (T_{surface} - gel)]$
Drying time	$t_{Dry} = \frac{Q_{dry}}{h_a \frac{A_{Drying}}{N_{batch}} (T_\infty^{oven} - T_{surface})}$
Drying rate	$\dot{m}_w^{evap} = \frac{m_w^{evap}}{t_{Dry}}$

Table S7. Individual Factors for Operating Cost Estimation.

	Name of Cost Item	Individual Factor
Manufacturing Cost (MC) <i>[M\$/year]</i>	Cost of Raw Materials ^{1,2,3,4}	$\sum m_i \times p_i$
	Direct Labour ^{3,4}	$N_{workstation} \times N_{shift} \times Salary$
	Indirect Labour ^{3,4}	$\sum N_j \times Salary_j$
	Utilities ^{1,2,3,4}	Mass and Energy balances
	Supplies ^{1,2,3,4}	$0.009 \times I$
	Maintenance ^{1,2,3,4}	$0.06 \times C_{Ph}$
	Laboratory ⁴	$0.20 \times Direct\ Labour$
	Depreciation (linear) ^{1,2,3,4}	$C_{Equipment}/12$
	Property taxes ⁴	$0.01 \times I$
	Insurance ^{1,2,3,4}	$0.01 \times I$
Management Cost (G) <i>[M\$/year]</i>	Marketing ^{1,2,3,4}	$0.15 \times C$
	Administrative Cost ^{3,4}	$1.10 \times (\sum N_k \times Salary_k)$
	Financing Cost ^{1,2,3,4}	$0.08 \times PT$
	Research and Development ⁴	$0.03 \times I$
	Hygiene & Quality Tech. ^{3,4}	$N_{technician} \times N_{shift} \times Salary$
	Head and Directives ^{3,4}	$\sum N_k \times Salary_k$
Operating Cost (C) = MC + G		

* HM (1) FI (2) DN (3) SP&MP (4)

Individual Factors Used for Manufacturing Plant cost estimation.

Table S.8. Individual Factors for Capital Estimation.

	Name of Cost Item	Individual Factor
Physical Capital (C_{Ph}) [M\$]	Cost of Equipment ^{3,4}	$\sum N_l \times p_l$
	Installation and Shipping ⁴	$\sum (N_l \times p_l \times F_l \times F_{shipping})$
	Piping ⁴	$0.45 \times C_{Equipment}$
	Measuring Instrumentation ⁴	$0.20 \times C_{Equipment}$
	Thermal Insulation ⁴	$0.07 \times C_{Equipment}$
	Electricity Facilities ^{3,4}	$0.15 \times C_{Equipment}$
	Building Expenses ⁴	$3 \times A_{Equip} \times C_{Edification}$
	Land Cost ⁴	$4 \times A_{Equip} \times C_{Indust Land}$
	Utilities Installation ^{3,4}	$0.40 \times C_{Equipment}$
	Refurbishment ³ (DSB, 2017)	$(1700 + 55 \times m^2_{kitchen} + 700) N_{kitchen}$
Deposit rent ³ (Quality, 2017)	$12 \frac{mo.}{year} \times 30 \frac{\pounds}{m^2 mo.} \times m^2_{kitchen} \times N_{kitch}$	
	Engineering and Supervision ⁴	$0.20 \times C_{Ph}$
Direct Capital (C_D)	$C_{Ph} + C_{Eng}$	
	Contractor's fee ⁴	$0.07 \times C_D$
	Contingency ⁴	$0.20 \times C_D$
	Previous Research ⁴	$0.12 \times I$
	Start-up Cost ⁴	$0.08 \times I$
Fixed Capital (I)	$C_D + C_{Cont fee} + C_{Conting} + C_{Prev Res} + C_{Star-up}$	
Working Capital (P_C) Time Basis: 1 Month	Pre-ordered Raw Mat and Utilities ⁴	$C_{Raw Mat}/q \times q/12$ $q \equiv annual prod [t/year]$
	Material under manufacture ⁴	$1/2 \times MC/q \times f \times q/12$ $f \equiv manufacturing cycle [y^{-1}]$
	Inventory ⁴	$MC/q \times q/12$
	Inventory ^{1,2,3}	$Operating Cost/52$
	Pending Sales ⁴	$1/2 \times V/q \times q/12$ $V \equiv Sales revenue [M\$ y^{-1}]$
	Cash in Bank ⁴	$MC/q \times q/12$
Total Capital (P_T) = $I + P_C$		

* HM (1) FI (2) DM (3) SP&MP (4)

Installation Factors for industrial equipment.

Table S.9. Installation factors for equipment (Silla, 2003).

Unit	Name in Silla's table	Installation Factor
Mills	Crushers, classifiers, mills	1.3
Dry Mixers	Blenders	1.3
Wet mixer	Blenders	1.3
Stirred tanks	Reactors, Kettles (CS)	1.9
Dryers	Dryers, other	1.4
Cooling	Miscellaneous	2.0
Package machine	Miscellaneous	2.0
Boiler	Boilers	1.5
Silos	Tanks, Storage (SS)	1.5
Intermediate tanks	Tanks, Storage (CS)	2.3

Wholesaling Cost of Raw Materials for Industrial Manufacture.

Table S.10. Prices of raw materials for industrial manufacture.

Raw material	Price (\$/t)	Source
Oat	241.13	Indexamundi, 2016a
Rice	460.10	Indexamundi, 2016b
Sugar	344.09	Indexamundi, 2016c
Skimmed milk powder	2574.00	Global Dairy Trade, 2016
Dry malt extract (food quality)	3500.00	Hunan Huacheng Biotech Inc, 2016
Palm oil flakes (food quality)	1045.00	Suoya Biological Technology, 2016
Water	2.57×10^{-3} (\$/m ³)	South West Water, 2016
Packing paper boxes	0.15 (\$/box)	Dongguan Fuliter Paper Prod., 2016
Packing cans	0.58 (\$/can)	XYN Can Packaging, 2016
Packing plastic boxes	0.20 (\$/box)	Shenzhen Huacheng Pack., 2016

Retail Cost of Raw Materials for Artisanal Manufacture.

Table S11. Supermarket raw materials price (Tesco, 2017).

Raw Material	Price (\$/kg)
Rice flour	1.58
Oat flour	2.64
Rice (raw)	1.97
Oat (raw)	0.99
Sugar	0.78
Milk powder	6.18
Dry malt extract	9.36
Vacuum bag (200 g)	0.21 \$/unit
Palm oil (food)	6.47

Price of energy sources.

Table S.12. Price and GHG conversion factors for different energy sources.

Fuel	Low Heating Value (kJ/kg) (Boundy, et al. 2011)	Price (£/kWh) (Government of United Kingdom, 2017b)	GHGs factor (kgCO ₂ e/kg) (Government of United Kingdom, 2017b)
Natural Gas	36,625 (kJ/m ³)	1.771 e-2	0.20463
Heavy Fuel Oil	38,700	3.830 e-2	0.28499
Diesel	42,791	4.423 e-2	0.26751
Coal	22,732	0.960 e-2	0.34149
Biomass (pellets)	17,209	5.033 e-2	0.01270
Electricity	-	8.363 e-2	0.41205

Labour Plant Manufacture Scale.

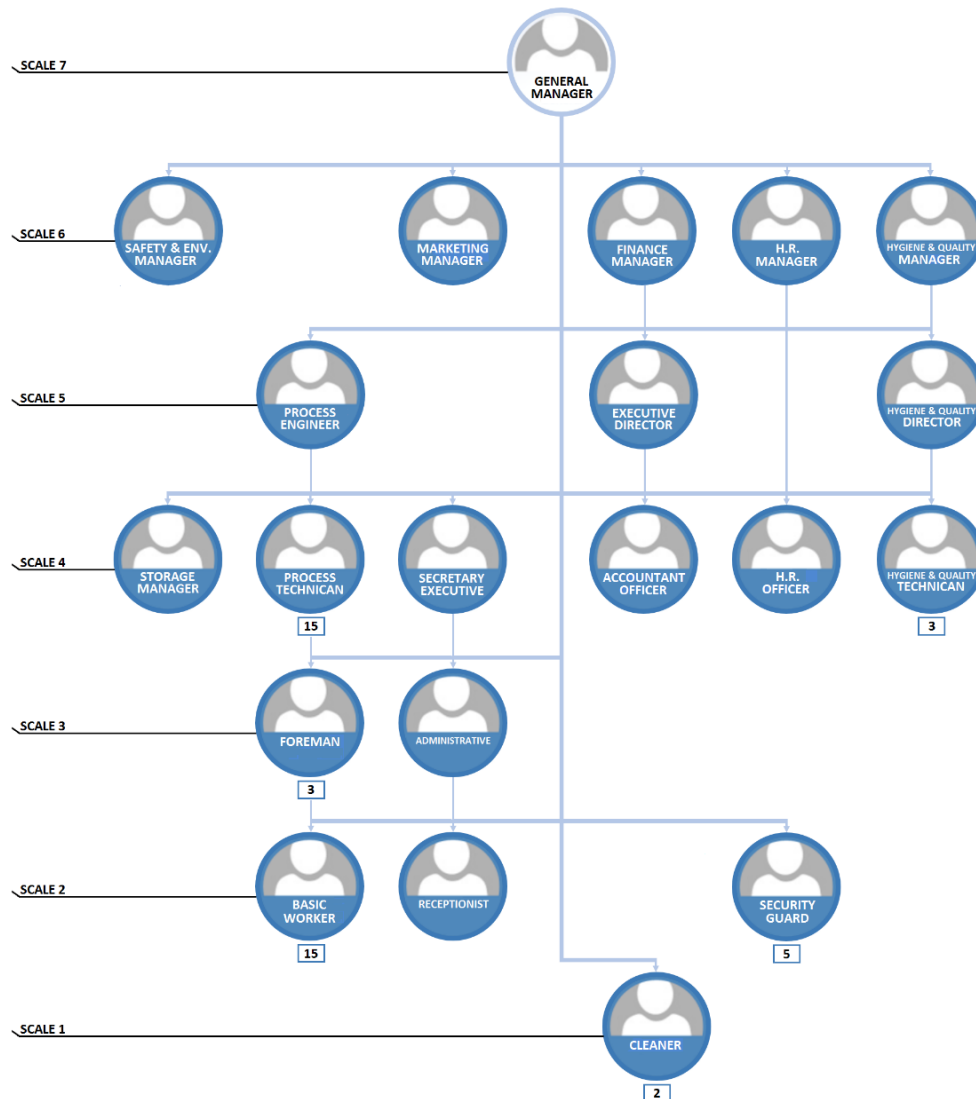


Figure S.1. Company Organisation Chart for Plant Manufacture.

Labour Plant Distributed Net Scale (High Manufacture Cost).

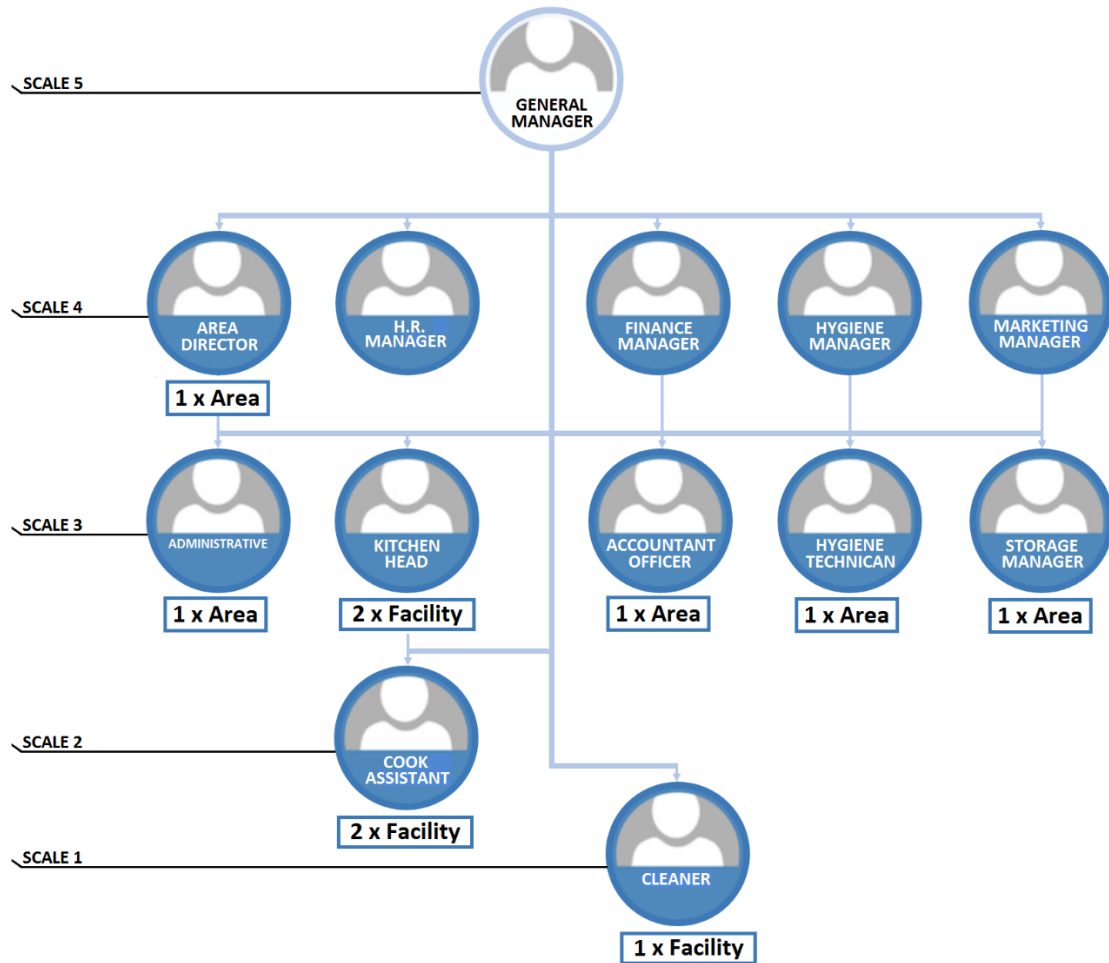


Figure S.2. Company Organisation Chart for Distributed Net with High Manufacture Cost.

Table S.13. Results of the mass and energy balances for Single-Plant scale in a scenario analogous to the UK.

STREAM	1	2	3	4	5	6	7
<i>Oat (kg/h)</i>	157.7	156.1	-	-	1.6	154.5	-
<i>Rice (kg/h)</i>	-	-	49.6	49.1	0.5	48.6	-
<i>Water (kg/h)</i>	-	-	-	-	-	-	812.4
<i>Palm oil (kg/h)</i>	-	-	-	-	-	-	-
<i>Sugar (kg/h)</i>	-	-	-	-	-	-	-
<i>Malt extract (kg/h)</i>	-	-	-	-	-	-	-
<i>Milk powder (kg/h)</i>	-	-	-	-	-	-	-
<i>Moisture (%)</i>	12.0	12.0	12.0	12.0	12.0	12.0	100.0
<i>Total mass (kg/h)</i>	157.7	156.1	49.6	49.1	2.1	203.1	812.4
<i>Temperature (k)</i>	293.2	293.2	293.2	293.2	293.2	293.2	293.2
<i>Pressure (bar)</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00
<i>Vapour quality</i>	0	0	0	0	0	0	0
<i>Heat (kJ/h)</i>	-	-	-	-	-	-	-

STREAM	8	9	10	11	12	13	14	15
<i>Oat (kg/h)</i>	1.5	153.0	1.5	151.5	-	3.8	147.7	147.7
<i>Rice (kg/h)</i>	0.5	48.1	0.5	47.6	-	1.2	46.4	46.4
<i>Water (kg/h)</i>	8.1	804.3	8.0	796.3	791.3	5.0	0	0
<i>Palm oil (kg/h)</i>	-	-	-	-	-	-	-	-
<i>Sugar (kg/h)</i>	-	-	-	-	-	-	-	-
<i>Malt extract (kg/h)</i>	-	-	-	-	-	-	-	-
<i>Milk powder (kg/h)</i>	-	-	-	-	-	-	-	-
<i>Moisture (%)</i>	82.6	82.6	82.6	82.6	100.0	82.4	10.6	10.6
<i>Total mass (kg/h)</i>	10.1	1,005.4	10.0	995.4	791.3	10.0	194.1	194.1
<i>Temperature (k)</i>	293.2	293.2	361.2	361.2	393.2	393.2	393.2	293.2
<i>Pressure (bar)</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
<i>Vapour quality</i>	0	0	0	0	1	0	0	0
<i>Heat (kJ/h)</i>	-	2.72×10^5			-3.41×10^4			-
		-			1.83×10^6			-

STREAM	16	17	18	19	20	21	22	23
<i>Oat (kg/h)</i>	-	-	-	-	-	-	-	146.1
<i>Rice (kg/h)</i>	-	-	-	-	-	-	-	45.8
<i>Water (kg/h)</i>	-	-	-	-	-	-	-	-
<i>Palm oil (kg/h)</i>	12.8	12.7	-	-	-	-	-	12.6
<i>Sugar (kg/h)</i>	-	-	85.2	84.3	-	-	-	83.6
<i>Malt extract (kg/h)</i>	-	-	-	-	4.2	4.2	-	4.2
<i>Milk powder (kg/h)</i>	-	-	-	-	-	-	126.5	125.2
<i>Moisture (%)</i>	0.0	0.0	1.8	1.8	2.0	2.0	2.5	6.0
<i>Total mass (kg/h)</i>	12.8	12.7	85.2	84.3	4.2	4.2	126.5	417.5
<i>Temperature (k)</i>	293.2	293.2	293.2	293.2	293.2	293.2	293.2	293.2
<i>Pressure (bar)</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
<i>Vapour quality</i>	0	0	0	0	0	0	0	0
<i>Heat (kJ/h)</i>	-	-	-	-	-	-	-	-

STREAM	24	25	26	27	W1	W2	W3
<i>Oat (kg/h)</i>	1.6	2,087 x (7.0 x 10 ⁻³ kg/pack h)	-	1.6	-	-	-
<i>Rice (kg/h)</i>	0.5	2,087 x (2.2 x 10 ⁻³ kg/pack h)	-	0.5	-	-	-
<i>Water (kg/h)</i>	-	-	-	-	614.6	614.6	614.6
<i>Palm oil (kg/h)</i>	0.1	2,087 x (6.0 x 10 ⁻³ kg/pack h)	0.1	-	-	-	-
<i>Sugar (kg/h)</i>	0.8	2,087 x (4.0 x 10 ⁻² kg/pack h)	0.9	-	-	-	-
<i>Malt extract (kg/h)</i>	4.2 x 10 ⁻²	2,087 x (2.0 x 10 ⁻³ kg/pack h)	4.2 x 10 ⁻²	-	-	-	-
<i>Milk powder (kg/h)</i>	1.3	2,087 x (6.0 x 10 ⁻² kg/pack h)	-	-	-	-	-
<i>Moisture (%)</i>	6.0	6.0	1.6	12.0	-	-	-
<i>Total mass (kg/h)</i>	4.3	2,087 x (0.20 kg/pack h)	300.0	2.1	-	-	-
<i>Temperature (k)</i>	293.2	293.2	293.2	293.2	431.9	431.9	373.9
<i>Pressure (bar)</i>	1.00	1.00	1.00	1.00	4.98	4.98	4.98
<i>Vapour quality</i>	0	-	0	0	1	0	0
<i>Heat (kJ/h)</i>	-	-	-	-	-1.83 x 10 ⁶		-2.72 x 10 ⁵

Table S14. Features and variables of design of all the units involved in Single-Plant manufacture. The design variable is given in the cost correlation units.

<i>Equipment</i>	<i>Feature 1</i>	<i>Feature 2</i>	<i>Design Variable</i>	<i>Power</i>
<i>Cage Mill (x4)</i>	<i>Length = 3.10 m</i>	<i>Width = 2.24 m</i>	<i>Diameter = 2.00 m</i>	<i>4.66 kW</i>
<i>Double Cone Blender (op. 2)</i>	<i>Length = 2.00 m</i>	<i>Width = 1.20 m</i>	<i>V = 5.30 ft³</i>	<i>2.24 kW</i>
<i>Ribbon Blender</i>	<i>Length = 1.63 m</i>	<i>Width = 0.71 m</i>	<i>V = 12.80 ft³</i>	<i>3.73 kW</i>
<i>Stirred Tank</i>	<i>Diameter = 0.60 m</i>	<i>Height = 1.20 m</i>	<i>V = 100.39 gal(US)</i>	<i>0.44 kW</i>
<i>Double Drum Dryer</i>	<i>Model #4 (x1)</i> <i>T_{Steam} = 139.7 °C</i>	<i>Rot Speed = 3.06 rpm</i> <i>M_{Steam} = 0.17 kg/s</i>	<i>Dry Surface = 135.30 ft²</i>	<i>17.31 kW</i>
<i>Cooling Conveyor</i>	<i>Length = 5.25 m</i>	<i>Width = 1.38 m</i>	<i>Q_{removed} = 6.80 kW</i>	<i>4.47 kW</i>
<i>Double Cone Blender (op. 8)</i>	<i>Length = 2.00 m</i>	<i>Width = 1.20 m</i>	<i>V = 5.30 ft³</i>	<i>2.24 kW</i>
<i>Pack. Machine</i>	<i>Length = 6.20 m</i>	<i>Width = 1.10 m</i>	<i>Cost = 58,000 \$/unit</i>	<i>3.70 kW</i>
<i>Steam Boiler</i>	<i>Diameter = 3.01 m</i> <i>IPS 4</i>	<i>81 tubes / 1 tube pass</i> <i>Fuel need = 97.8 m³/h</i>	<i>Capacity = 2500 lb/h</i>	<i>Natural Gas</i>
<i>Oat Silo</i>	<i>Diameter = 3.30 m</i>	<i>Height = 13.20 m</i>	<i>Weight = 36,970 kg</i>	<i>-</i>
<i>Rice Silo</i>	<i>Diameter = 1.95 m</i>	<i>Height = 7.80 m</i>	<i>Weight = 8,629 kg</i>	<i>-</i>
<i>Sugar Silo</i>	<i>Diameter = 2.85 m</i>	<i>Height = 11.40 m</i>	<i>Weight = 24,527 kg</i>	<i>-</i>
<i>Milk Powder Silo</i>	<i>Diameter = 2.85 m</i>	<i>Height = 11.40 m</i>	<i>Weight = 24,527 kg</i>	<i>-</i>
<i>Malt Extract Silo</i>	<i>Diameter = 1.05 m</i>	<i>Height = 4.20 m</i>	<i>Weight = 1,675 kg</i>	<i>-</i>
<i>Palm Oil Silo</i>	<i>Diameter = 1.65 m</i>	<i>Height = 6.60 m</i>	<i>Weight = 5,497 kg</i>	<i>-</i>
<i>Oat Flour Tank</i>	<i>Diameter = 0.45 m</i>	<i>Height = 0.90 m</i>	<i>Weight = 124 kg</i>	<i>-</i>
<i>Rice Flour Tank</i>	<i>Diameter = 0.30 m</i>	<i>Height = 0.60 m</i>	<i>Weight = 49 kg</i>	<i>-</i>
<i>Mixed Flour Tank</i>	<i>Diameter = 0.45 m</i>	<i>Height = 0.90 m</i>	<i>Weight = 122 kg</i>	<i>-</i>
<i>Wet Slurry tank</i>	<i>Diameter = 0.75 m</i>	<i>Height = 1.50 m</i>	<i>Weight = 421 kg</i>	<i>-</i>
<i>Dry and Cold Slurry Tank</i>	<i>Diameter = 0.45 m</i>	<i>Height = 0.90 m</i>	<i>Weight = 122 kg</i>	<i>-</i>
<i>Final Pre-Packed Product Tank</i>	<i>Diameter = 0.60 m</i>	<i>Height = 1.20 m</i>	<i>Weight = 243 kg</i>	<i>-</i>

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