Centralized and distributed food manufacture

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

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Abstract

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

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1. Introduction

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

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

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

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

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

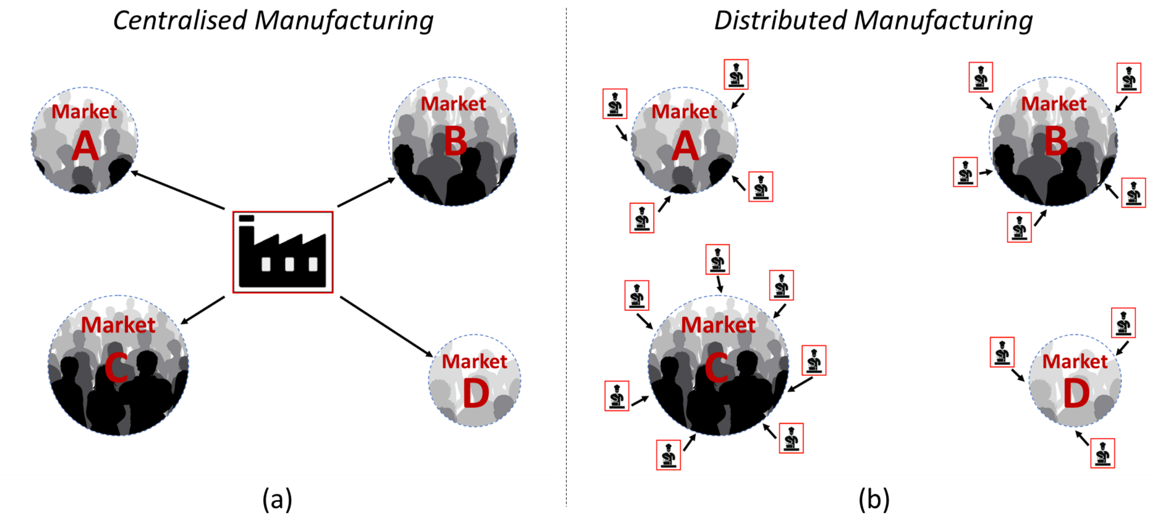


Figure 1: Food product supply chain. (a) Centralized Manufacturing (scenario A) vs. (b) Distributed Manufacturing (scenario B). A net of manufacturing facilities replaces a big plant for supplying the demand of a product in four different markets.

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

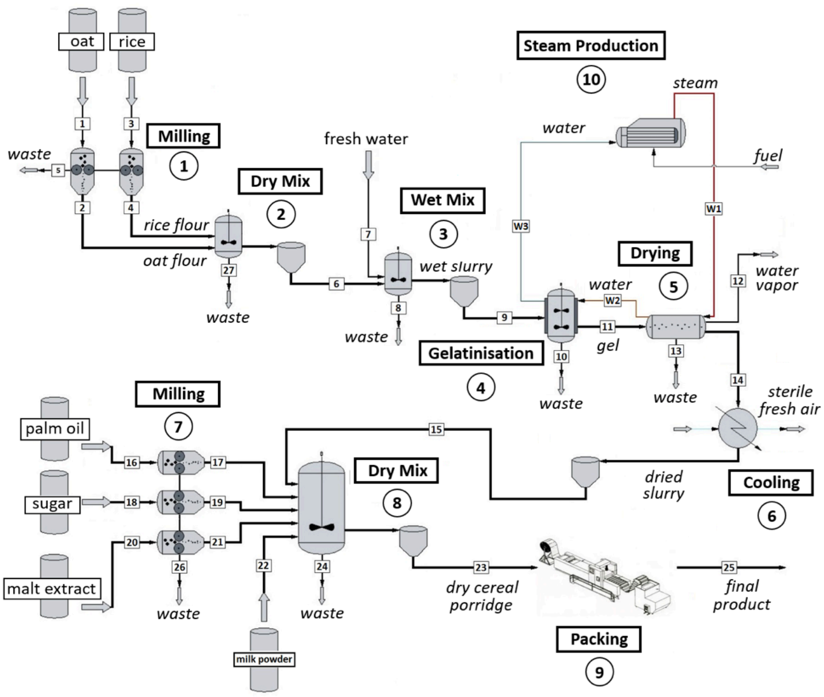
2. Characterization of different manufacturing scenarios

2.1. General description of the manufacture process

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

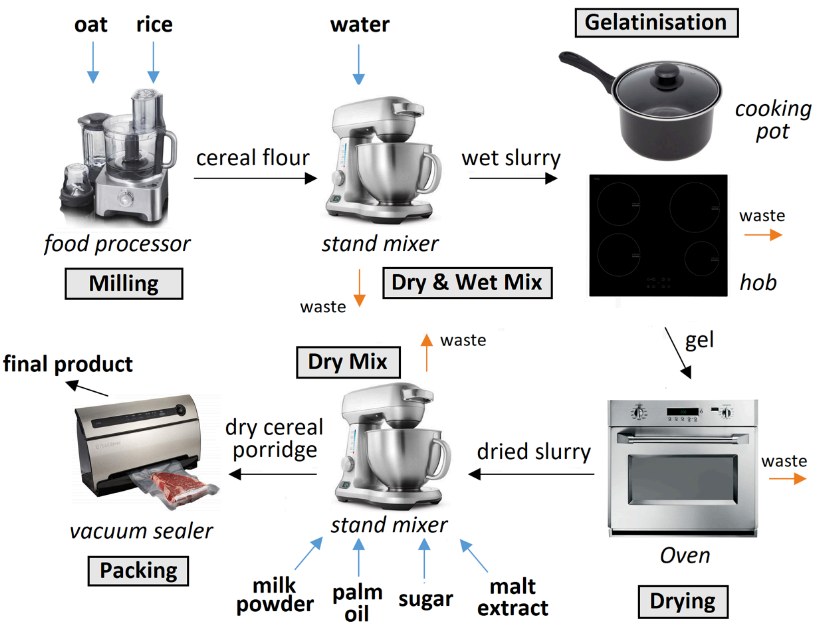
This requires changes in the equipment (see Figure 2(b)) and other manufacturing aspects, e.g. batch operation. Further equipment details (e.g. prices, dimensions, capacities) are provided in the Supplementary Material (see Table S.1, Table S.2 and Table S.3).

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



(a)

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.



(b)

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

2.2. Production scenarios

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

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

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

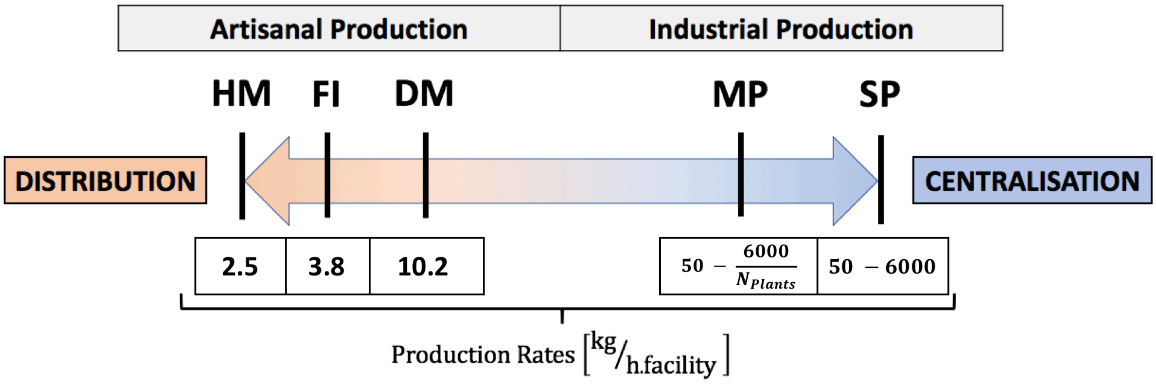


Figure 3: Schematics representing the production methods and scale considered in this work. HM: Home Manufacturing, FI: Food Incubator, DM: Distributed Manufacture, SP: Single Plant, MP: Multiple Plant. The production rate numbers respond to the manufacturing scales designed on this work. N_{Plants}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

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

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

3. Model description

The model describes the manufacture of dry cereal porridge based on both industrial and artisanal manufacturing flowsheets. This allows the scale-down and comparison of the different scenarios studied at a range of production rates (from 0.5 kg/h up to 6000 kg/h). The whole set of equations includes mass and energy balances - used to design the process unit operations (i.e. drying) and evaluate energy demand - economic analysis and carbon footprint estimation. The viability of each production scenario is assessed using the calculated profits and environmental impacts obtained as model outcomes. Overall, the model consists of 40 decision variables, 800 parameters, 2500 equations and has been implemented on Matlab®.

3.1. Model assumptions.

3.1.1. General assumptions

- The water content of the cereal flour, milk powder, sugar and malt extract considered in the moisture mass balances is 12.0% (The Quaker Oats Company, 1984), 2.5% (Reh et al., 2004), 1.75% (Bitjoka et al., 2007), and 2.0% (Lancaster, 1923) respectively.
- The waste for mixing (dry and wet), gelatinization, milling and drying, is taken a value of 1% of the unit inflow.
- Greenhouse gas emission (GHG) are estimated from calculated energy demand using the corresponding energy conversion factors (Government of the United Kingdom, 2017c). These factors estimate the emissions, i.e. environmental impact, associated to different activities such as burning fuels and electricity consumption (see Table S.12 in the Supplementary material for values).
- The selling format for is a baby food pouch of 0.2 kg.

3.1.2. Industrial production method assumptions

- The time for plant/s annual operation is 16 hours/day for 48 weeks, 5 days a week (2 shifts) (Maroulis and Saravacos, 2008), closed for 4 weeks for maintenance.
- Equipment size depends on plant throughput. Mass balances provide information of the capacity that each unit must have.
- Mills, blenders, stirred tank and storage units are oversized using security factors (Walas, 1990). The chosen unit is the one with the next-higher volume found on the

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

- Different efficiencies for the boilers and burners are assumed during the operation, depending on the fuel: 72.5% for natural gas, 76.0% of heavy fuel oil and diesel, 80.0% for coal and 65.0 % for biomass (CIBO, 2003).
- The condensed steam obtained from the drying stage is used to heat the slurry in the gelatinization stage, giving some heat integration.

3.1.3. Artisanal production assumptions

- Artisan methods (i.e. HM, FI and DM) are based on batch processes, with only the drying stage overlapping.
- Milling, mixing and gelatinization times are assumed the same as in Industrial Production. Packing time for HM is considered as 30s per sealed pouch –see Table 1.
- The working day for single worker scenarios –i.e. HM and FI– is 8h per day (1 shift). DM is assumed to comprise two shifts per day, reaching 16 h/day of operation. The three artisan scales operate for 48 weeks, 5 days a week, as for Industrial Production.
- For HM, only one piece of each equipment is available. The batch size is therefore the volume of one food processor, i.e. 1.5×10^{-3} m^3. Solution of the corresponding schedule problem leads to a single batch size of 25 pouches of 0.2 kg, four being the maximum number of batches per day.
- FI and DM facilities provide more than one piece of equipment. The initial batch volume for both scenarios is 3.0×10^{-3} m^3. A maximum of three batches of 51 pouches can be produced in a working day by a single worker for FI. DM throughput per facility depends on the number of ovens considered.

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

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

Unit Operation	Main Conditions	Equipment: Industrial Production (Fig. 2)	Equipment: 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

- HM has no building cost associated as the activity is developed on the worker's kitchen. In the FI case, a monthly payment (kitchen fee) has been added to the operating cost. For DM, the kitchens are rented, assuming a surface of 20m^2 per unit.
- HM uses existing personal kitchen instrumentation. However, depreciation of this capital is considered for future replacement of equipment due to use. For FI, no fixed capital is assumed as both equipment and building are rented.
- Initial investments, i.e. working capital, are considered equal to the operating cost of one week, the same as inventory cost.

3.2. Mass and energy balances

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

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

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

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

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

$$\mathrm{Cp_{prod}} = \sum_{i}^{n} \mathrm{x}_i * \mathrm{Cp}_i \quad (3)$$

$$\dot{Q}_{tot} = \dot{Q}_{sensible} + \dot{Q}_{latent} = \dot{M} * Cp_j * \Delta T + \dot{M} * \Delta H^{evap} \tag{4}$$

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

3.3. Drying operations

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

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

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

3.4. Cost estimation

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

3.4.1 Total capital

Total capital was defined as the total investment required for construction and start-up, i.e. cost of the equipment, piping and instrumentation, building and land charges, project fees, start-up, contingency and working capital. The equipment purchase and installation is estimated using correlations from Matches' Process Equipment Cost Estimates database (Matches, 2014), and installation factors (see Table S.1 and Table S.9 in the Supplementary Material). Building and land surfaces are estimated assuming an area of three and four times the area occupied by the equipment, thus including safety distances (Mecklenburgh, 1973). Building and land areas are then costed using average cost in the UK (Government of United Kingdom, 2015; Jewson, 2017) –1029.3 $\$/m^2$ and 482,000 £/hectare (66.2 $\$/m^2$). For DM fixed capital comprises the refurbishment of kitchens, cost of instrumentation, purchase of auxiliary materials (utilities factor) and one-year rent as deposit.

3.4.2 Production cost

The total production (or operating) cost is defined as the annual expense related to manufacture. It comprises: raw materials and packages, electricity and fuel, direct and indirect labor, utilities, supplies, maintenance, laboratory cost, depreciation of the equipment, property taxes, insurance and management cost. Prices of the raw materials are listed in Table S.10 (industrial method) and Table S.11 (artisanal method) in the Supplementary Material. Energy prices are also in the Supplementary Material (see Table S.12). Labor cost, equipment depreciation and management cost are not computed using individual factors.

3.4.3 Labor cost and equipment depreciation

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

3.4.4 Management cost

For HM and FI scenarios, examples of the 'gig-economy', management is carried out by the company. This follows the approach of Uber® and Airbnb® in other sectors, costing a fee of 20% (Huet, 2015) over the baby cereal porridge sales revenue. The seller is the main responsible for the quality and hygiene of the product, as must follow the food hygiene regulations set by the government. The company in charge of management (e.g. the analogous to Uber) would also seek for the highest quality of the products to protect the brand, so part of the management fee would be used to meet the food quality and safety standards, and developing new techniques and products. Management cost at DM and SP/MP scales comprises different items (see Table S.7). Individual factors used for the Industrial Process are shown. For DM, management is necessary to ensuring proper performance of the scattered manufacturing facilities. As a first approach, marketing cost includes the overhead costs of the product (Peters and Timmerhaus, 2003). Quality and hygiene must be controlled and increase the management cost. Due to the degree of complexity, two levels of management have been considered. The lower bound considers each facility as a local business where the owner must fulfil all the standards set by the UK Food Standards Agency (FSA) –i.e. a franchise model– with the supervision of the company that provides the brand. For the upper bound, a single company manages the whole business. Specialized technicians are constantly in charge of the food security and quality with two visits per month at each facility. Facilities are divided up to areas with an assumed maximum of 10 branches, with managers in charge of each area (see Figure S.2).

3.5 Net profit calculation

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

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

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

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

4. Results and Discussion

The designed tool generates data for different scenarios. For each, it provides cost estimation, design of equipment, number of facilities and labor requires, energy demand and GHG emissions associated, etc. Different manufacturing scales are compared by finding operating cost per kilogram of product manufactured over the full range of scales. The profitability of one scale over the others is therefore set by the cost per unit, assuming the selling price is constant.

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

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

4.1. Effect of the production scale on the operating cost

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

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

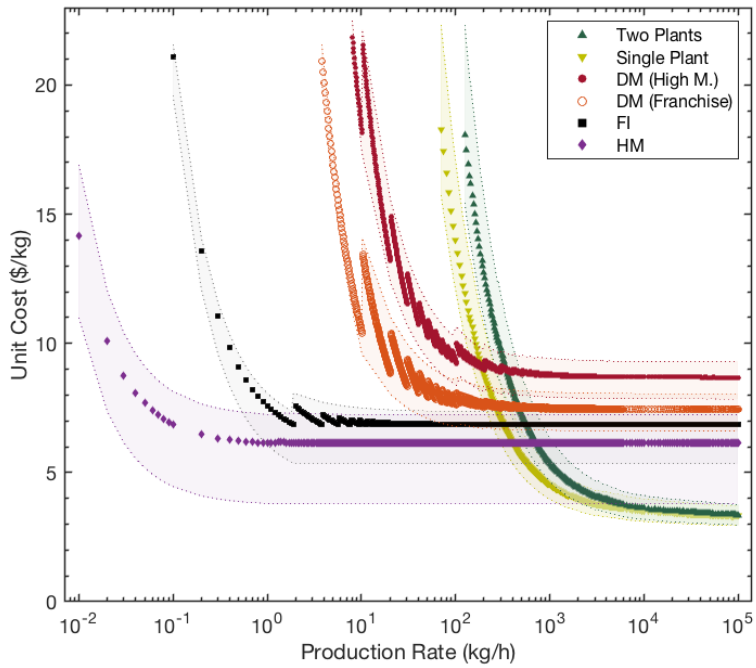


Figure 4: Variation of the unit cost with throughput for different production scales. Unit costs above 10 $/kg (assuming UK market prices) incur in economic loss and thus result in non-profitable production scenarios. According to this, SP is not profitable above 200 kg/h; DM range of operation is profitable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

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

4.1.1 Breakdown of the unit cost

The operating cost per unit has been broken down and analyzed. Costs can be classified as variable and fixed. Variable cost items –e.g. raw materials and package cost– increase with throughput. However, variable cost per unit of product is constant. Fixed cost items are independent of production rate and so fixed cost per unit depends on the production rate studied. The overall fixed cost is different for each production scale, increasing with the size of the manufacturing facilities. HM has depreciation of instrumentation as a fixed cost which becomes very expensive at extremely low production rates. The unit cost rapidly decreases as more product is produced. For FI, fixed cost is related to the food incubator fee and the share on the total unit cost is higher than HM. Therefore, this approach requires more product units to spread the fixed cost, i.e. the feasible region starts at higher production rates. DM involves higher fixed cost than the two previous manufacturing scales. Each facility requires labor, rent, instrumentation and management cost; as a result, DM requires higher demand scenarios (ca. 30 kg/h assuming low management) for profitability. The solution for the three artisan manufacturing scenarios shows a maximum when an additional facility is required, and then the effect of that expense is lowered until the maximum capacity is reached. The amplitude is greater as the scale of manufacturing increases, when it requires a higher injection of fixed cost. However, the amplitude of the step decreases with increasing throughput values, as shown in Figure 4. This is also an effect of spreading the fixed cost over a higher number of units produced.

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

4.1.2 Unit cost sensitivity analysis

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

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

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

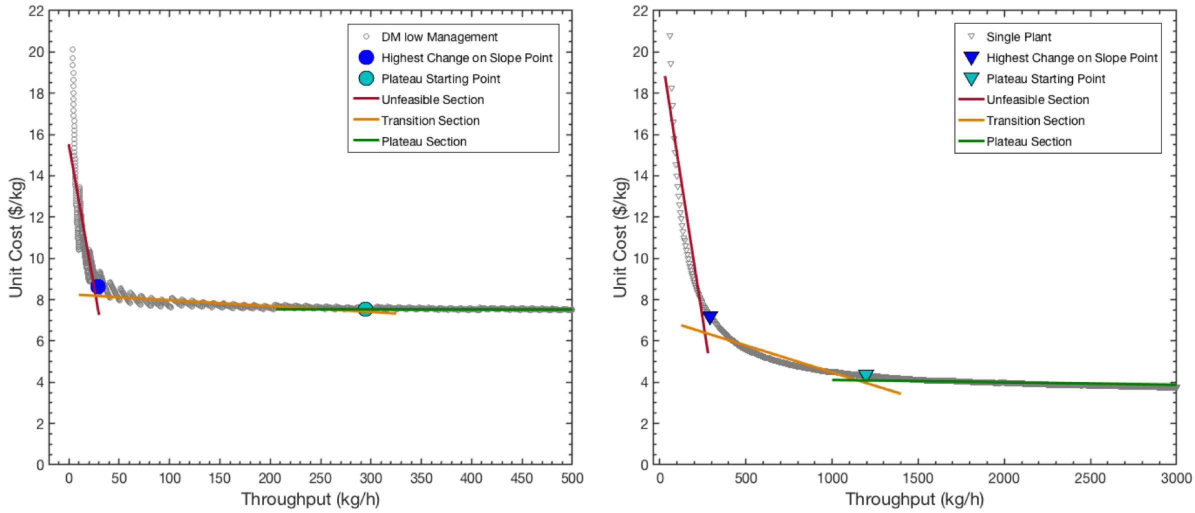
Table 2: Crossover points from Figure 4 for each manufacturing scale, including uncertainties: lower bound (lb) and higher bound (hb). A pair of values is associated to each intersection. The upper value corresponds to the x-axis coordinate (*throughput – kg/h*), while the lower is the y-axis coordinate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

- 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.

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

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



(a) (b)

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.

HCS and the PR points divide the data in three recognizable regions. The left section comprises the points with the highest slope, where a small increase in the production leads to a significant cost reduction. The scenario is non-feasible, as any profit-seeking company would increase the investment for a greater production if it is cost effective. When the first characteristic point is reached, achieving cost reduction requires a higher increase on productivity, i.e. an important capital injection. Scenario within the transition section, between HCS and PR, could be feasible if it is profitable. The right region represents the plateau, where there is no cost reduction from increasing the production rate. Profits grow with the number of product units sold, so companies with no limit on investment and enough market share will invest in bigger production scenarios.

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

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

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

HM and FI reached this point for one operating facility, while DM does it for the third and fifth facility depending on the management. For industrial production in single plant and two plants, they are reached at similar overall production rates (≈ 300 kg/h) but at a greater operating cost for the latter. Both HM and SP reach transition region at similar cost values around 7.3 $/kg, but at a throughput difference of four orders of magnitude (0.06 and 290 kg/h respectively). PR points are reached at higher production rates than HCS, but showing a similar behavior. Although the fall in cost for industrial manufacturing scenarios when the plateau appears is higher (4.35 for SP and 4.70 for 2P), it is reached at a very high production rate, nearly three and four times the entire demand of dry baby food in the UK for SP and 2P respectively. On the other hand, artisan manufacturing scenarios achieve all their cost effectivity potential at lower production rates. The cost and throughput values when a plateau is reached increase with the size of the facility. HM does it at 7 kg/h (7 operating facilities) at a cost slightly above 6.1 $/kg and FI when 17 facilities are working with a cost under 6.7 kg/h.

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

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

4.3. Effect of manufacturing scale on total capital

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

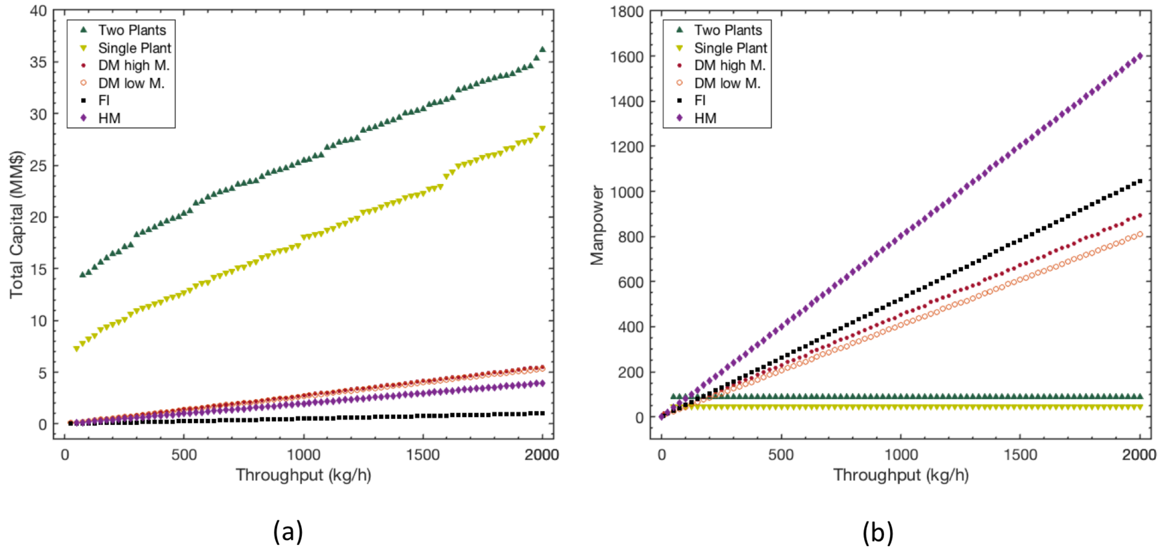


Figure 6: (a) Total capital and (b) Manpower required for each production scale at different final product´s production rates. Industrial manufacture requires a much larger investment than artisanal production scales, as depicted in (a). Furthermore, the greater number of facilities for small scales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

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

Figure 6(b) show the manpower needed at each production rate. Industrial manufacturing labor remains constant, as plants require the same personnel. If two plants are considered, the manpower increases, although not doubling as the senior management is shared. For artisanal manufacturing scenarios, the lowest the scale the highest the manpower required. HM and FI comprise one worker per facility and has the steepest slopes of Figure 6(b). However, being representative of 'gig-economy', labor does not involve any cost as they are the beneficiaries of the economic activity. DM manpower is assumed to be salaried employees, representing the most significant contribution to unit cost for this manufacturing scale. Labor cost becomes even greater those scenarios that include more management personnel.

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

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

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

4.4.1 Total capital

Total capital corresponding to each UK-based scenario is presented in Figure 7(a). Results show the effect of initial investments (e.g. machinery, land or buildings), as artisanal manufacturing scenarios exhibit much lower values than the industrial scenarios. For example, the DM scenario requires as initial investment the 9.6% of SP capital. The increase in capital required to go from single plant (12.1 MM$) to two plants is 7.4 MM$ (61.4%). When scaling from two plants to three, the rise is smaller –6.4 MM$ (34%)– and increases again when adding an additional plant –7.1 MM$ (26%).

4.4.2 Unit operating cost

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

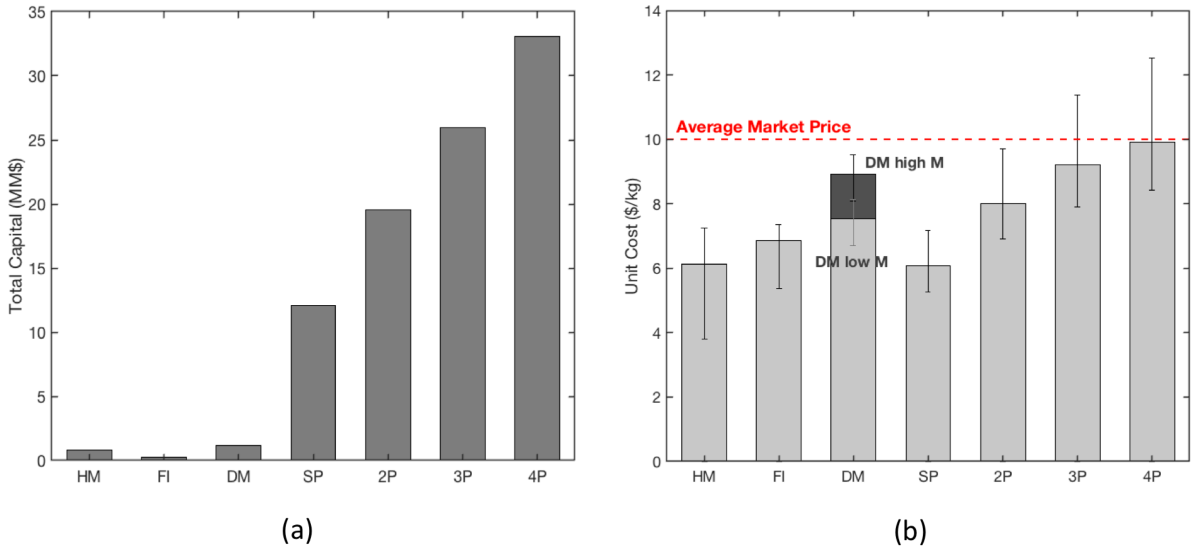


Figure 7: Total capital (a) and unit operating cost (b) for HM, FI, DM, SP and MP production scenarios under UK dry baby food demand (418 kg/h). In (b) DM has two unit operating cost values for high management (dark bar section and franchise (light bar section). Error bars show the uncertainties for 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.

4.4.3 Net profit

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

4.4.4 Energy demand and carbon footprint at manufacture stage

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

The carbon footprint for on each scenario was estimated from calculated energy using the UK Government Greenhouse Gas (GHG) Conversion Factors (Government of the United Kingdom, 2017c). This provides the GHG emissions data that every manufacturer must report to the UK government. The carbon footprint of the industrial process is the lowest, producing 0.530 kg CO_2e per kg of product manufactured, as shown in Table 4. An additional plant increases the emissions by 4% as the energy efficiency slightly drops.

Among the alternative fuel sources, a boiler fed with biomass (pellets) carries the least carbon footprint, despite being less energy effective. The use of this kind of boiler at industrial scale is still challenging. For the alternative manufacture methods, environmental impact factors related to these scenarios give emissions around 15% higher than industrial ones. HM carries the least emissions within artisanal manufacture with 0.596 kg CO_2e/kg. FI and DM slightly increase the carbon load by 2% and 3%. If electric ovens are used for drying, the energy demand decreases by 40% from natural gas, but the environmental impact rises by 33%.

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

Manufacturing Scenario	Total Energy	Electricity Consumption	Fuel Consumption	$C_{Electrici}$	C_{fuel}	C_{Total}
	$kJ/_{kg}$	$kWh/_{kg}$	$kg/_{h}$	$kg\ CO_{2e}/_{kg}$		
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 $\left(m^3/_{h}\right)$	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 $\left(m^3/_{h}\right)$	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

5. Overview and future food manufacture trends and challenges

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

At the smallest manufacturing scale per facility, a very large number of "production units" (labor and stores) is required to duplicate the output of a plant, which can generate new jobs and stronger social impacts in local communities. However, the concept of the 'gig-economy', understood as "crowdwork" or "work-on demand via app", eliminates boundaries for manpower, enhancing market flexibility, albeit at the cost of economic security for many workers (Dokko et al., 2015). Advances in information and communication technologies (ICT) have allowed the contact of an indefinite number of costumers and workers on a global basis (De Stefano, 2016), and the additional concept of a 'sharing economy' (also called 'collaborative consumption'), which involves peer-to-peer based activity of sharing the access to goods coordinated by ICTs (Hamari et al., 2016), has overcome the limitation of capital investment at low production rates. These ideas set the basis for different manufacturing models on food processing, by analogy with other industry sectors, e.g. Uber and Airbnb. Modular manufacturing (Baldea and Edgar, 2017) and additive manufacturing (Femmer et al., 2015) are different up-to-date approaches for seeking a decentralized, scalable and flexible production in other sectors of the industry, consolidating these new trends.

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

6. Conclusions

A model-based tool for the design, simulation and cost estimation of manufacturing process at several scales of production has been developed and used to assess the profitability of four different scenarios, from decentralized manufacturing (HM, FI and DM) to centralized manufacturing (SP and MP), in the production of a dried food. Operating regions, namely unfeasible, transition and plateau, have been identified for each manufacturing scale. Crossover points showing the boundaries of operation for decentralized scales to be more profitable than industrial scenarios are also predicted. Results show that total decentralization (HM and FI), can be an alternative to centralization by providing competitive operating cost and increased manpower. The DM scenario represents a competitive alternative to the current centralized production, when its management cost is moderate. The low capital required and the sensible number or facilities comprising the net suggest this could be easier to apply at the UK scale. For energy use and carbon load, artisanal manufacture-based scenarios are not advantageous when compared to the industrial processing. Results revealed that splitting the production into two or more plants does not give any advantage for manufacturing in economic terms.

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

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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
	$C_{MSCI}(\$_{2016}) = C_{MSCI}(\$_{2014}) \dfrac{IM\&S_{2016}}{IM\&S_{2014}}$	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 ℃)*
$\frac{1}{U} = \frac{1}{h_{i_0}} + r_{di}\frac{d_0}{d_i} + \frac{1}{\kappa_{drum}} + r_{d0} + \frac{1}{\kappa_{d-s}}$
Mean condensation film coefficient inside horizontal tubes *(W /m^2 ℃)* (Sinnot and Towler, 2013)
$\mathrm{h}_{\mathrm{i}_0} = 0.76\ k_L \left[\frac{\rho_L(\rho_L - \rho_V)g}{\mu_L\ \Gamma_h}\right]^{1/3}$
Conduction coefficient for the dryer drum *(κ_m [=] W /m ℃ ; d_0 [=] m)*
$\kappa_{drum} = \frac{2\ \kappa_m}{d_0 \ln\left(d_0/d_i\right)}$
Conduction coefficient for the drum *($\kappa_{slurry\ gel}$ [=] W /m ℃ ; $\tau_{slurry\ gel}$ [=] m)*
$\kappa_{d-s} = \frac{\kappa_{slurry\ gel}}{\tau_{slurry\ gel}}$
Internal fouling resistance *(m^2 ℃ / W)* (Sinnot and Towler, 2013)
$r_{di} = 1/f_{steam} = 1/3250$
External fouling resistance *(m^2 ℃ / W)* (Sinnot 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 *(℃)*
$\Delta T_{lm} = \frac{\left(T_{steam} - T_{Dry}\right) - \left(T_{Steam} - T_{Gel}\right)}{log\left[\frac{\left(T_{steam} - T_{Dry}\right)}{\left(T_{Steam} - T_{Gel}\right)}\right]}$
Drying rate *(kg/s)*
$\dot{m}_w{}^f = \left(Q_{drum} - Q_{sensible\ gel}\right)\Big/\Delta H_{vap}{}^{H_2O}$
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
$J_{DD} = \sqrt{\sum\left(x_w{}^f - x_w{}^{target}\right)^2} + \sqrt{\sum\left(\dot{m}_w{}^f - \dot{m}_w{}^{target}\right)^2} + \left(\frac{1}{1000}\right)\sqrt{\sum\left(Q_{drum} - Q_{dry}\right)^2}$

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}	$Model \, \# \, \omega_{drum}{}^{min}$	$Model \, \# \, \omega_{drum}{}^{max}$

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 $\{(C_{dd} + C_b)\}$

Table S.6. Domestic convective oven operation

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

Table S7. *Individual Factors for Operating Cost Estimation.*

	Name of Cost Item	Individual Factor
Manufacturing Cost (MC) *[M$/year]*	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) *[M$/year]*	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)	$(1700 + 55 \text{ x } m^2_{kitchen} + 700)\ N_{kitchen}$
	Deposit rent[3] (Quality, 2017)	$12 \frac{mo.}{year} \text{ x } 30 \frac{£}{m^2 mo.} \text{ x } m^2_{kitchen} \text{ x } N_{kitch}$
	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 ($/t)	Source
Oat	241.13	Indexmundi, 2016a
Rice	460.10	Indexmundi, 2016b
Sugar	344.09	Indexmundi, 2016c
Skimmed milk powder	2574.00	Global Dairy Trade, 2016
Dry malt extract (food quality)	3500.00	Hunan Huacheng Biotech Inc, 2016
Palm oil flakes (food quality)	1045.00	Suoya Biological Technology, 2016
Water	2.57×10^{-3} ($/m3)	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 ($kgCO_2e/kg$)** (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.

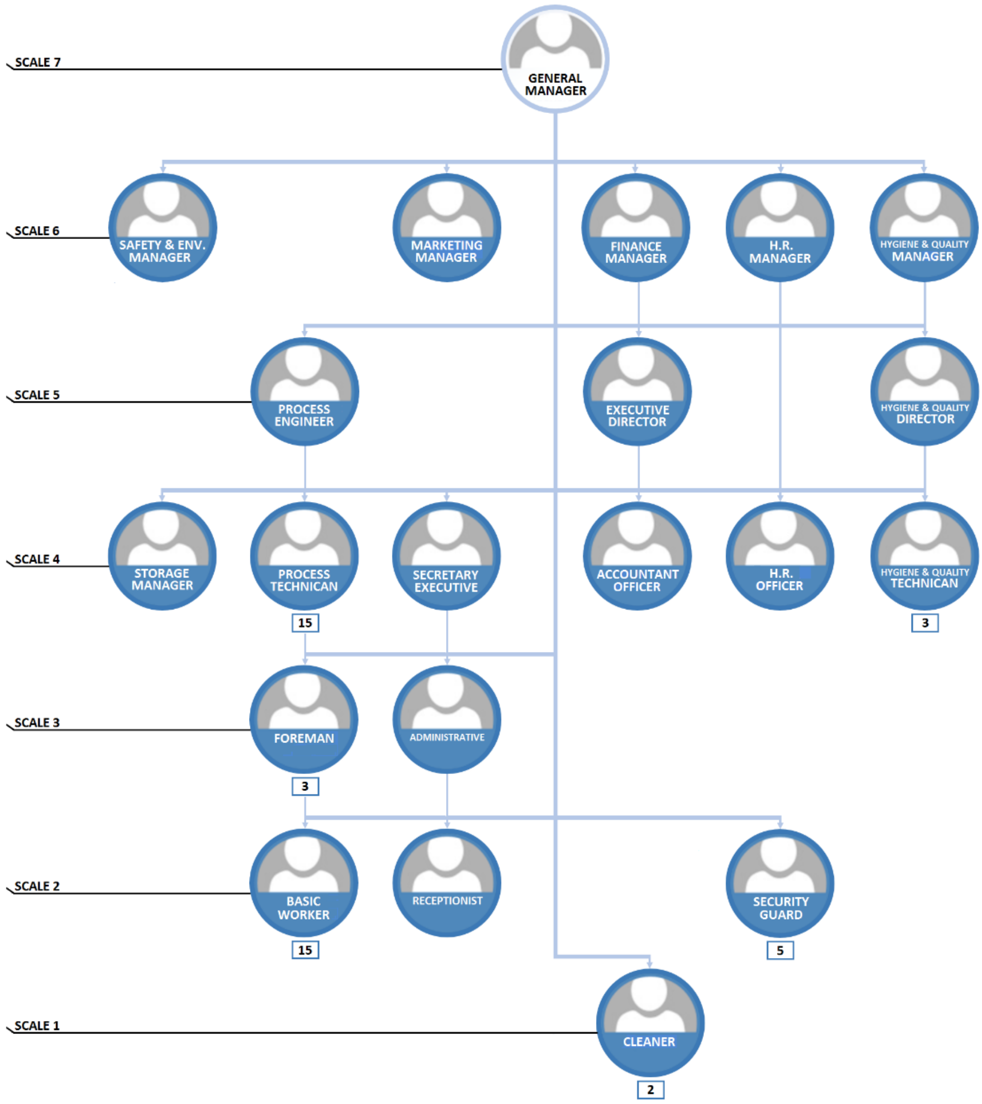

Figure S.1. *Company Organisation Chart for Plant Manufacture.*

Labour Plant Distributed Net Scale (High Manufacture Cost).

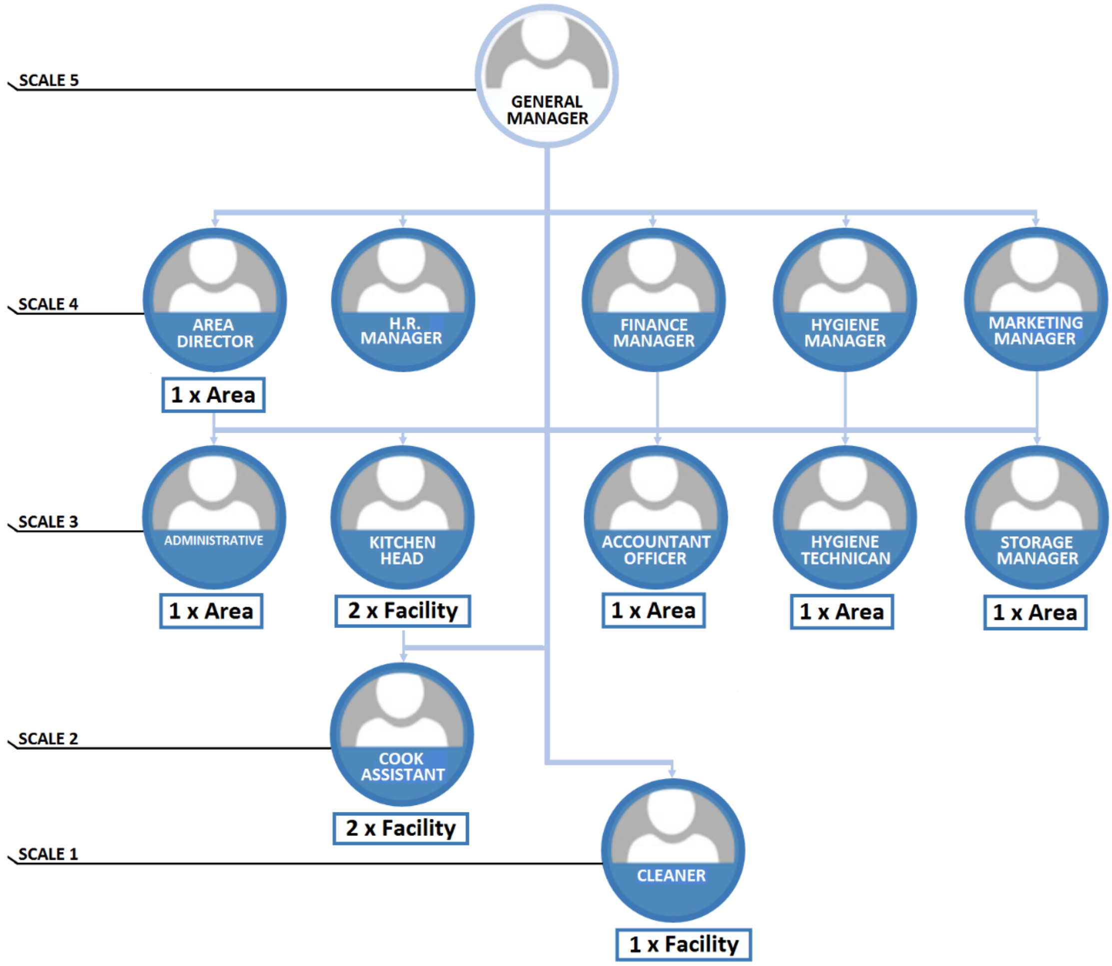

Figure S.2. *Company Organisation Chart for Distributed Net with High Manufacture Cost.*

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**
Oat (kg/h)	157.7	156.1	-	-	1.6	154.5	-
Rice (kg/h)	-	-	49.6	49.1	0.5	48.6	-
Water (kg/h)	-	-	-	-	-	-	812.4
Palm oil (kg/h)	-	-	-	-	-	-	-
Sugar (kg/h)	-	-	-	-	-	-	-
Malt extract (kg/h)	-	-	-	-	-	-	-
Milk powder (kg/h)	-	-	-	-	-	-	-
Moisture (%)	12.0	12.0	12.0	12.0	12.0	12.0	100.0
Total mass (kg/h)	157.7	156.1	49.6	49.1	2.1	203.1	812.4
Temperature (k)	293.2	293.2	293.2	293.2	293.2	293.2	293.2
Pressure (bar)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Vapour quality	0	0	0	0	0	0	0
Heat (kJ/h)	-	-	-	-	-	-	-

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

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

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

Equipment	***Feature 1***	***Feature 2***	***Design Variable***	***Power***
Cage Mill (x4)	*Length = 3.10 m*	*Width = 2.24 m*	*Diameter = 2.00 m*	*4.66 kW*
Double Cone Blender (op. 2)	*Length = 2.00 m*	*Width = 1.20 m*	*V = 5.30* ft^3	*2.24 kW*
Ribbon Blender	*Length = 1.63 m*	*Width = 0.71 m*	*V = 12.80* ft^3	*3.73 kW*
Stirred Tank	*Diameter = 0.60 m*	*Height = 1.20 m*	*V = 100.39 gal(US)*	*0.44 kW*
Double Drum Dryer	*Model #4 (x1)* T_{Steam} *= 139.7 °C*	*Rot Speed = 3.06 rpm* M_{Steam} *= 0.17 kg/s*	*Dry Surface = 135.30* ft^2	*17.31 kW*
Cooling Conveyor	*Length = 5.25 m*	*Width = 1.38 m*	$Q_{removed}$ *= 6.80 kW*	*4.47 kW*
Double Cone Blender (op. 8)	*Length = 2.00 m*	*Width = 1.20 m*	*V = 5.30* ft^3	*2.24 kW*
Pack. Machine	*Length = 6.20 m*	*Width = 1.10 m*	*Cost = 58,000 $/unit*	*3.70 kW*
Steam Boiler	*Diameter = 3.01 m IPS 4*	*81 tubes / 1 tube pass Fuel need = 97.8* m^3/h	*Capacity = 2500 lb/h*	*Natural Gas*
Oat Silo	*Diameter = 3.30 m*	*Height = 13.20 m*	*Weight = 36,970 kg*	-
Rice Silo	*Diameter = 1.95 m*	*Height =7.80 m*	*Weight = 8,629 kg*	-
Sugar Silo	*Diameter = 2.85 m*	*Height = 11.40 m*	*Weight = 24,527 kg*	-
Milk Powder Silo	*Diameter = 2.85 m*	*Height = 11.40 m*	*Weight = 24,527 kg*	-
Malt Extract Silo	*Diameter = 1.05 m*	*Height = 4.20 m*	*Weight = 1,675 kg*	-
Palm Oil Silo	*Diameter = 1.65 m*	*Height = 6.60 m*	*Weight = 5,497 kg*	-
Oat Flour Tank	*Diameter = 0.45 m*	*Height = 0.90 m*	*Weight = 124 kg*	-
Rice Flour Tank	*Diameter = 0.30 m*	*Height = 0.60 m*	*Weight = 49 kg*	-
Mixed Flour Tank	*Diameter = 0.45 m*	*Height = 0.90 m*	*Weight = 122 kg*	-
Wet Slurry tank	*Diameter = 0.75 m*	*Height = 1.50 m*	*Weight = 421 kg*	-
Dry and Cold Slurry Tank	*Diameter = 0.45 m*	*Height = 0.90 m*	*Weight = 122 kg*	-
Final Pre-Packed Product Tank	*Diameter = 0.60 m*	*Height = 1.20 m*	*Weight = 243 kg*	-

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