UNIVERSITY OF BIRMINGHAM
University of Birmingham Research at Birmingham

Towards the decentralisation of food manufacture

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

DOI:
10.1016/j.egypro.2019.02.080

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Almena Ruiz, A, Lopez-Quiroga, E, Fryer, P & Bakalis, S 2019, 'Towards the decentralisation of food manufacture: effect of scale production on economics, carbon footprint and energy demand', *Energy Procedia*, vol. 161, pp. 182-189. https://doi.org/10.1016/j.egypro.2019.02.080

Link to publication on Research at Birmingham portal

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 19. Apr. 2024

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 161 (2019) 182–189

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2018, 17-19 October 2019, Paphos, Cyprus

Towards the decentralisation of food manufacture: effect of scale production on economics, carbon footprint and energy demand

A.Almena[a], E. Lopez-Quiroga[a], P.J. Fryer[a]*[*], S. Bakalis[b]

[a]*School of Chemical Engineering. University of Birmingham, B15 2TT, United Kingdom*
[b]*Faculty of Engineering, The University of Nottingham, NG7 2RD, United Kingdom*

Abstract

Most food products are currently processed in large, centralised factories with delocalised retail systems, which allows food processors benefit from economies of scale. This is efficient in terms of production, but can involve lengthy and rigid supply chains, with higher transport costs and environmental impacts. Decentralised manufacturing, based on local production at small scale, has risen recently as an alternative that could provide flexibility to the food supply chain. In this work we present a modelling tool for the design, evaluation and comparison of food manufacturing processes that considers economic, environmental and social factors. The proposed method can be applied to a wide range of food products and is illustrated here using cereal porridge and sandwich bread production. We have assessed and compared three decentralised scenarios: "Home Manufacturing" (HM), "Food Incubator" (FI) and "Distributed Manufacturing" (DM) to centralised production –i.e. Single Plant (SP) and Multi Plant (MP) scenarios. Based on UK demand, SP is the most energy efficient and cheapest scenario in both cases, closely followed by HM and FI in cereal porridge production. DM could compete with SP assuming low management costs and savings on transportation/storage along the supply chain. For the case study on bread, the shorter margin of profit per unit makes decentralised scenarios less advantageous.

Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018

Keywords: descentralization; distributed; food; manufacturing; footprint; scale-down.

---

* Corresponding author. Tel.: +44-121-4145451.
E-mail address: p.j.fryer@bham.ac.uk

1876-6102 © 2019 The Authors. Published by Elsevier Ltd.

Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018.
10.1016/j.egypro.2019.02.080

Nomenclature

CM	Centralised Manufacturing	HM	Home Manufacturing
DM	Distributed Manufacturing	MP	Multiple-Plant Manufacturing
FI	Food Incubator	SP	Single Plant Manufacturing

1. Introduction

The Industrial Revolution enabled the combination of machinery with sources of power, concentrating production in large factories. This new paradigm of manufacturing –i.e. *Centralised Manufacturing* (CM)– allowed processors to exploit the benefits of economies of scale, reducing costs and increasing market share [1]. Large-scale production led to a standardisation of the product and – lengthy [2] – supply chains arose, with a small number of processing plants supplying national, or even multinational, demand. Although cost-efficient in terms of production, this centralised manufacturing system also implied inflexibility on the production [3] and significant costs [4] and environmental impacts linked to transportation. Currently, efforts and resources are aimed at improving distribution/transport efficiency and reducing both *food miles* and carbon footprint associated to CM scenarios [5], and in this way satisfy the eco-demand of modern societies [6]. In this context of change, Decentralised Manufacturing scenarios - which is characterised by customisation (i.e. flexible production), shorter delivery times, reduced transportation costs and agility [4] - represents a promising alternative to many of CM drawbacks. Modular Manufacturing [7] and Additive Manufacturing [8], both based on decentralised systems, can be mentioned as emerging examples of this shift on manufacturing methodologies.

The Food Industry, which is the largest sector in the UK contributing £113 billion (6.4%) to the Gross Value Added in 2016 [9], has also followed the same trend, and most of the food products are now produced in large food plants and shipped long distances for retail. The UK food supply chain consumes 367 TWh (18% of total energy) and is responsible for 147 Mt CO2 e. emissions (15% of total in UK) [9]. Therefore, the search for alternative manufacturing methods that help to decrease environmental burdens is critical also for the Food sector. In this framework, Distributed Manufacturing (DM), based on decentralised small-scale production and location close to customers [2] has revealed as a potential alternative to centralised food production. Drivers for this change include new technologies, rising logistics costs, changing global economies and environmental, social and ethical policies [10] - for example, implementing DM as the production stage of Short Food Supply Chains [11] has the potential to lead to ‘good food network’ [12]. Also, craft production at small scale can provide fresh, customised and locally distributed food, so energy use related to distribution and storage can be reduced [2].

In this framework, we present here a novel model-based for the analysis and comparison of these different manufacturing scenarios that are needed. This methodology combines design of food process unit operations with economics analysis and uses the profitability and the environmental impact of each scenario as measures for its viability. The main objective of this work is to define those production scale scenarios where DM might become more advantageous – both economically and environmentally. This tool also makes possible scaling-down production scenarios, where diseconomies of scale might become more evident. The model use is illustrated through two case studies (i) manufacture of dry cereal porridge (reconstitutable with the addition of water or milk) and (ii) manufacture of sliced bread.

2. Methodology

Small-scale manufacturing scenarios as the ones defined by DM are incompatible to large plant production. Fig. 1(a) represents how total cost typically varies with production at plant scale manufacturing. Fixed cost remains constant regardless the production rate –e.g. straight-line depreciation of machinery is the same producing 100 or 1000 units/h. Conversely, variable cost increases with the throughput value –e.g. raw materials purchase doubles up for producing the double number of units. This trend is inverted for the cost per unit of product: fixed costs per unit become too expensive at low throughput and drive the unitary cost above the market price leading to non-profitable scenarios, as shown in Fig. 1(b). In this scenario, variable cost per unit remains constant and the well-known benefits of economies of scale, i.e. the fixed cost is spread over more units of production, no longer hold [13].

2.1 Manufacturing methods

Two different manufacturing methods are considered in this work: industrial and artisanal production. Table 1 lists the most representative production conditions and equipment for each case. The former is based on the operation of a process line. The artisanal method keeps the same unit operations, but at smaller scales of production. This requires changes in the equipment and other manufacturing aspects, e.g. batch operation.

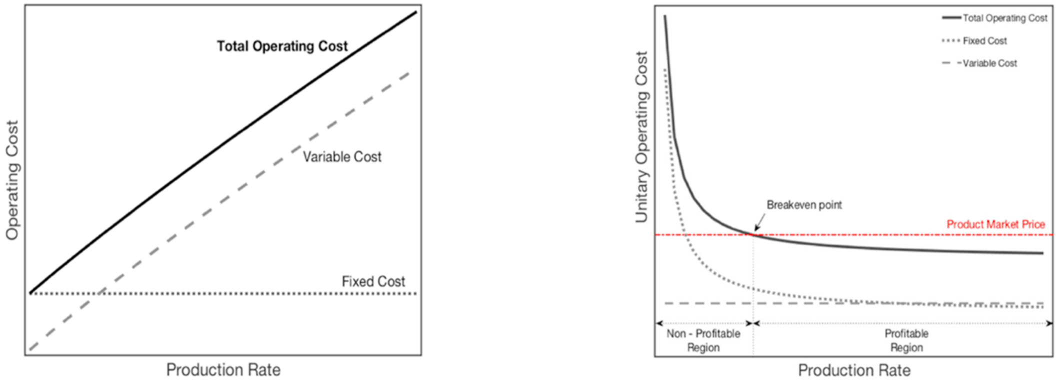

Fig. 1. (a) Operating Cost and (b) Operating cost per unit of product behaviour at manufacturing stage. Breakeven point divides the operation in profitable and non-profitable regions. The increasing share of fixed cost at low throughput make the operating cost surpass the breakeven point.

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

Cereal Porridge				*Sliced Bread*				
Unit Operation	**Main Conditions**	**Industrial Production**	**Artisanal Production**	**Unit Operation**	**Main Conditions**	**Industrial Production**	**Artisanal Production**	
							DM	**FI & HM**
Milling	5 min	Cage mill	Food processor	***Mixing***	2min 150rpm 6min 360rpm	Ribbon Blender	Spiral Mixer	Stand Mixer
Dry mixing (1)	15 min	Double Cone Blender	Stand Mixer	***Dividing***	2 min/batch^{DM} 30 s/loaf^{FI,HM}	Volumetric Pressure Divider	Hydraulic Divider	Kitchen Scale
Wet mixing	Moisture 80 w%	Ribbon Blender		***First Proof***	10 min Temp ambient	Spiral Proofer	Natural Resting	Natural Resting
Gelatinisation	T = 88 °C 20 min	Jacketed Stirred Tank	Cooking Pot	***Moulding***	30 s/loaf^{FI,HM}	Conical Rounder & Bread Maker	Bread Moulder	Manual Moulding
Drying	Moisture: up to 6 w%	Double Drum Dryer	Domestic Oven	***Final Proof***	50min/30 min 37 °C	Spiral Proofer	Proofing Cabinet	Natural Proofing
Cooling	Atmospheric Temperature	Refrigerated Belt Conveyor	Natural Cooling	***Baking***	20 min^{SP,MP} 240 °C	Tunnel Oven	Rack Oven	Convection Oven
Dry mixing (2)	15 min Sterile atmosphere (industrial)	Double Cone Blender	Stand Mixer	***Cooling***	7400 s^{SP,MP} 600 s^{FI,HM} 20 °C	Cooling Tower	Natural Cooling	Natural Cooling
Packing	30s/pouch	Packing Machine	Vacuum Sealer	***Slicing***	30 s/loaf^{FI,HM}	Slicing Machine	Bread Slicer	Home Slicer
				Packing	30s/loaf^{FI,HM}	Packing Machine	Manual Packing	Manual Packing

2.1. Production Scenarios

Four different scenarios for food have been considered [14]. They go from highly decentralised distribution to centralised manufacturing:

i) Home Manufacturing (HM): This is based on an "on-demand" economy model (e.g. Uber). In this scenario, it is assumed that a group of cooks produce the food (1 worker per kitchen) and sell it on-demand.

ii) Food Incubator (FI): this is a "sharing economy" scenario, where a group of cooks rent suitable premises and specialised equipment.

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

iv) Single and Multiple Plant Production (SP, MP). The fourth scenario represents a centralised manufacturing scenario, with a big industrial plant –or a number of them.

2.2. Model Description

The model combines the design of food process unit operations with economics analysis and uses the profitability and the environmental impact of each scenario as measures for its viability. The definition of different manufacturing methods, i.e. artisanal and industrial, allows the scale-down and comparison of the different production scenarios studied. The resulting model consists of 40 decision variables, 1500 parameters, 4500 equations, and has been solved using Matlab®.

Main model assumptions: Artisanal scenarios are based on batch production, while the industrial ones operate in continuous. The size of the batches and the mass rates of the continuous processes have been based on literature data and industrial machinery catalogues. Cost variables (e.g. raw material and energy prices, labour costs) as well as environmental indexes have been taken from updated sources. UK average market price for each product is used to assess profitability. Cereal porridge production rates range from 0.01 kg/h up to 6000 kg/h while for sliced bread higher production rates (up to 35,000 kg/h) has been considered, according to market demand. Final moisture content in the cereal porridge was set to 6%. The ready-to-sell loaf of bread weights 0.8g.

Mass and energy balances: The input data for equipment design is given by mass balance and residence time (see Table 1). Energy balance outcomes provide the heat supply for each unitary operation. Thermal processes used to remove water from the food matrices (i.e. drying, baking) represent the most energy intensive manufacturing stages. For cereal porridge industrial manufacture, the operation of a double drum-dryer has been modelled [15] and used to define efficient operation modes that lead to required final moisture contents. For industrial bread scenarios, the energy demand of the tunnel oven has been approximated by using literature data [16], while for the artisanal cases residence times where estimated from energy demand and overall heat transfer coefficients [17]. At plant scales, heat integration has been also considered.

Economic and environmental evaluation: Total capital and operating cost, including multiple cost items [18], are computed for each manufacturing scale. This allows to study the profitability of different manufacturing scenarios, to assess the effect of the manufacturing scale on those economic factors and to monitor their evolution for a chosen throughput range. Uncertainties, regarding variations price fluctuations, capital cost or marketing costs are considered [14]. Finally, the carbon footprint associated to each manufacturing scenario was also computed.

3. Results and discussion

3.1. Effect of production scale on unitary costs.

Fig.2(a) and 2(b) show unit costs for cereal porridge and bread, respectively, as a function of the production rate (kg/h). The shaded areas in the graphs indicate the uncertainty ranges (variations price fluctuations, capital cost or marketing costs). Results reveal the same trends for all manufacturing scales: at low production rates, the operating cost presents the steepest slope. Then, it keeps flattening out until a plateau is eventually reached. Those plateaus appear at higher production rates for bread manufacturing, due to the higher contribution of fixed cost to the overall production cost.

At artisan manufacturing scales, the maximum production capacity of a single facility shows discontinuities when an additional kitchen is necessary. For industrial manufacturing, those steps correspond to bigger equipment or extra processing lines. The lower market price of bread (1.32 \$/loaf), compared to porridge one (10 \$/kg), allows a smaller profit margin. HM shows profitability at very low production rates for porridge and bread, reaching a minimum operating cost of 6.13 \$/kg and 0.83 \$/loaf respectively. For FI, the increase on the cost due to the rent of the kitchen is the same for both products. However, bread manufacture makes a lower value-added product and therefore the share of the kitchen fee is higher, so the FI curve differs more from HM and the profit margin is lower. This is also supported by the greater amplitude of the steps on the bread discontinuous function. The plateau sets a price of 6.86 \$/kg and 1.09\$/loaf.

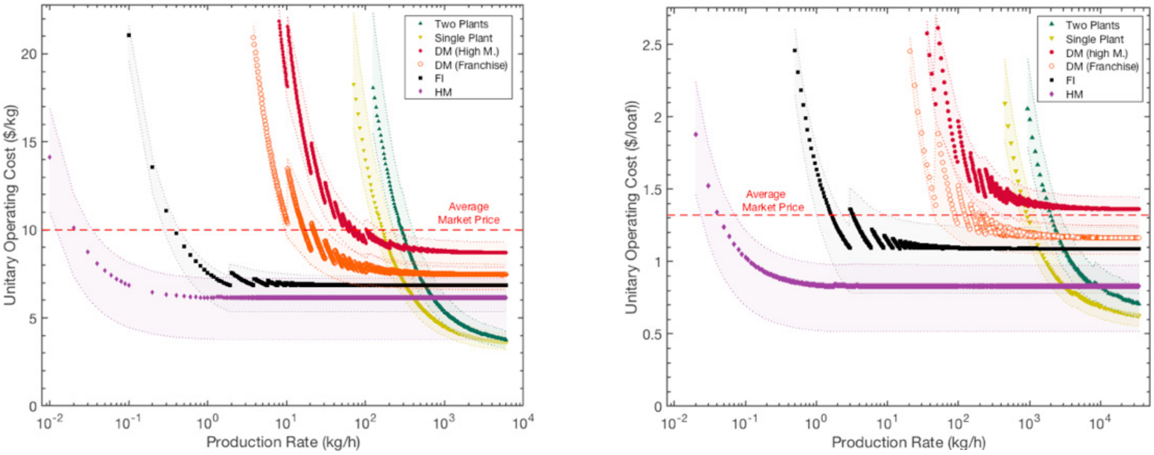

Fig. 2 (a): Variation of cereal porridge unitary cost with throughput for different production scales. Costs above 10 \$/kg result in economic losses assuming UK market price. SP scenario is not profitable below 200 kg/h; DM range of operation is widened down to 60 kg/h (high management) and 20 kg/h (franchise - low management). HM and FI remain profitable at very low production rates. Fig. 2(b): Variation of bread unitary cost with throughput for different production scales. Costs above 1.3 \$/loaf result in economic losses assuming UK market price.

A DM scenario is always the most expensive method for artisanal manufacturing. Whilst for the latter DM is profitable for both high and low management assumptions –plateau at 7.57 \$/kg and 8.80 \$/kg respectively–, for bread only the franchise model cost –plateau at 1.16 \$/loaf– remains below the market price. This makes it necessary to increase the selling price of the loaf to balance costs.

Regarding plant manufacturing, there are no significant difference between cereal porridge and bread manufacture in terms of fixed cost at similar throughputs. However, the higher cost of raw materials and packaging for porridge manufacturing, i.e. more than 120% higher than bread case, makes the variable cost share higher, reaching the plateau values at higher operating costs (4.70 \$/kg). On the other hand, bread processing plant scenarios need higher production rates to balance the share of fixed cost and reduce unitary costs. According to this, profitability in SP scenarios is reached at throughputs higher than 200kg/h for porridge, and higher than 1000 kg/h for bread. In both cases, halving the production in two plants increases manufacturing cost. MP scenarios are considered feasible - compared to SP ones - when uncertainties overlap.

3.2. UK demand case study: profitability.

The estimated UK annual consumption of the cereal porridge considered in this work is approx. of 1600 tonnes, while for sliced bread that figures increases up to 190,000 tonnes/year [14]. According to this demand data, a plant output of 418 kg/h and 23,560 kg/h is needed to satisfy such demand of cereal porridge and bread, respectively. This difference in demand leads also to different operation times for plant manufacturing scenarios: two shifts are considered in the cereal porridge case study (i.e. 16 h/day, 5 day/week, 48 week/year), while three shifts operating also during weekends (i.e. 24 h/day, 7 day/week, 48 week/year). For HM and FI, production is based on a single shift: 8 h/day, 5 day/week and 48 week/year; DM annual operation is calculated using two shifts. The number of facilities comprising each scenario was computed accordingly.

Table 2 presents number of facilities, unitary costs, capital and profits for all the manufacturing scenarios operating to satisfy UK demands of cereal porridge and sliced bread. In both cases, SP is the cheapest scenario. However, HM provides similar production cost, especially for cereal porridge. The difference on the value of the final product makes FI and DM less profitable for bread than for cereal porridge manufacture. Model results show a non-profitable scenario for porridge manufacture for the DM case under high management assumptions. At the industrial scales, splitting the demand between two plants is less profitable due to the effects of economies of scale. This effect is more significant for the porridge case, with a 32% increase on operating cost for SP scenarios.

The total capital needed for artisanal manufacturing is substantially lower than for industrial based scenarios: e.g. DM requires 10% of SP investment for cereal porridge and 33% for bread. FI uses rented facilities and assets, so the capital comprises only inventory costs. In HM, the workers use their own kitchen equipment, which has been here included as assets – damages must be covered also by the workers themselves.

Table 2: Economic evaluation results for all manufacturing scenarios considered in the production of cereal porridge and sliced bread at UK demand levels.

Manufacturing Scenario	*Baby Cereal Porridge (418 kg/h)*				*Sliced Bread (23,560 kg/h)*			
	Number of Facilities	Unitary Cost ($/kg)	Total Capital (M$)	Net Profit (M$)	Number of Facilities	Unitary Cost ($/loaf)	Total Capital (M$)	Net Profit (M$/year)
HM	334	6.13	0.8	5.0	13089	0.83	20.7	93.5
FI	219	6.85	0.2	4.0	7854	1.09	5.1	43.7
DM (franchise)	41	7.52	1.1	3.2	491	1.16	43.6	29.9
DM (high Management)	41	8.92	1.2	1.4	491	1.36	44.5	- 7.9
SP	1	6.06	12.1	5.1	1	0.64	132.3	129.3
MP (Two)	2	8.01	19.5	2.6	2	0.73	146.9	112.0

Finally, industrial manufacturing shows the highest net profit. Sliced bread scenario, despite the selling price is lower, shows more profitable due to the higher number of units sold. However, when comparing the net profit per operating facility, bread manufacture shows lower values (see Fig.3). Taking as an example the annual earnings of DM -franchise-, an operating facility producing sliced bread has 60,500 $/year as annual earnings. For baby cereal porridge, that value increases to 78,000 $/year (29% more) as a higher value-added good is produced. For the same reason, the feasibility of HM and FI in bread case study is not clear. The earnings are 7,100 $/year and 5,600 $/year respectively, so the selling price might need to be increased.

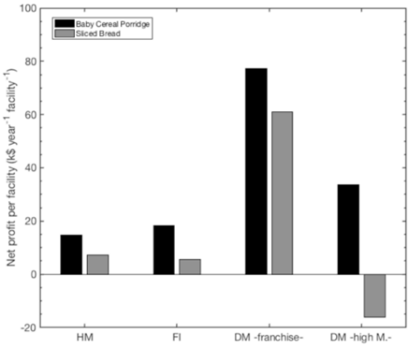

Figure 3. Net profit per facility for artisan manufacturing scenarios. Bread case study show lower profitability per unit.

3.3. UK demand case study: energy demand and carbon footprint

The effect of scale production on energy demand and carbon footprint has been also evaluated for all the manufacturing scenarios considered in this work. For artisan manufacturing methods, both electric and gas convection ovens are considered (see Table 3). For plant manufacturing, gas and fuel oil are used to operate the boilers (Table 3). Based on the energy demand model results and fuel impact factors in the UK [19], the corresponding environmental impact factor of each production scenario was estimated. Table 3 shows the results for the two food products assessed in this work, assuming a scenario similar to UK demand.

Single plant processing is more energy effective than the artisanal when a gas oven carries out the drying step. The difference is higher for bread manufacturing, where DM uses 47% more energy than industrial (6% for porridge). FI and HM show less energy consumption, the latter being the most energy effective from all the artisan manufacturing scenarios. When comparing both products, sliced bread process is more energy effective at both artisanal and industrial scales: manufacturing of bread requires only 25-28% of cereal porridge energy per kilogram of product at artisanal scales, while represents approx. 20% of the cereal energy demand at industrial scale. The higher amount of water to be removed (i.e. evaporated) from porridge slurries (typically above 60%) is responsible for such significant difference on energy consumption. Energy demand increase resulting from the addition of a second plant is also higher for the case of cereal porridge manufacture.

According to this, the specific carbon load ($kgCO_2e\ kg^{-1}$) associated to bread is therefore lower than the porridge one (see Table 3). However, in the artisanal manufacturing of cereal porridge, the electricity share -when gas oven is used- is higher than in bread case. For both products, artisan manufacturing methods using gas ovens lead to lower carbon footprints than drying/baking processes using electric ovens.

Table 3: Carbon Footprint of HM, FI, DM, SP and MP (2 plants) at the manufacturing stage for both case studies, in a scenario similar to UK demand.

Manufacturing Scenario	*Baby Cereal Porridge (418 kg/h)*				*Sliced Bread (23,560 kg/h)*			
	Total Energy	Electricity Consumption	Fuel Consumption	Carbon Load	Total Energy	Electricity Consumption	Fuel Consumption	Carbon Load
	kJ kg^{-1}	kWh kg^{-1}	$m^3\ h^{-1}$	$kgCO_2e\ kg^{-1}$	kJ kg^{-1}	kWh kg^{-1}	$m^3\ h^{-1}$	$kgCO_2e\ kg^{-1}$
HM								
-electric oven-	7002.0	1.945	–	0.801	1790.6	0.497	–	0.205
-gas oven-	9086.0	0.208	95.0	0.560	2344.3	0.036	1424.9	0.141
FI								
-electric oven-	7077.2	1.966	–	0.810	1800.0	0.500	–	0.206
-gas oven-	9120.3	0.263	93.2	0.573	2353.7	0.039	1424.9	0.142
DM								
-electric oven-	7059.2	1.961	–	0.808	1948.4	0.541	–	0.223
-gas oven-	9102.3	0.258	93.2	0.571	2581.2	0.014	1628.4	0.150
SP								
-natural gas boiler-	8946.0	0.102	97.8	0.530	1761.5	0.061	991.1	0.113
-fuel oil boiler-	8550.9		88.3 (kg h^{-1})	0.690	1752.8		869.6 109.7 (kg h^{-1})	0.116
MP (Two)								
-natural gas boiler-	9117.1	0.149	97.8	0.549	1763.2	0.062	991.1	0.113
-fuel oil boiler-	8722.0		88.3 (kg h^{-1})	0.709	1754.4		869.6 109.7 (kg h^{-1})	0.117

4. Conclusions

A modelling tool for the design, simulation and cost estimation of manufacturing food processes has been presented. This tool has been employed to evaluate unitary costs, profitability, energy demand and environmental impacts associated to the manufacture of cereal porridge and sliced bread at different manufacturing scales. The main objective of this work was to assess the potential of emerging decentralised/distributed manufacturing scenarios compared to the current centralised paradigm. The most decentralised scenario, i.e. HM based on an "on-demand" economy model, is profitable at very low production rates and proves to be competitive at high throughput to the most centralised scenario (SP). The latter, however, is the most cost-effective but requiring high investment and production rate. The comparison between the two food products has revealed that decentralised scenarios work better for high value-added goods, i.e. DM and FI is less profitable for bread than porridge. A practical scenario similar to UK demand has been also assessed. The lower selling price for bread decrease the net profit per facility for all decentralised scenarios.

The energy demand and carbon footprint for each scenario was also computed. Bread processing resulted in lower energy consumption and carbon load per kg produced. Different energy sources (electricity, gas and fuel oil) were also considered, showing that the use of natural gas leads to lower carbon footprints - even despite the lower energy efficiency of gas-fed instrumentation. Industrial manufacturing has proved to be the most environmentally-friendly manufacturing scenario. However, only a further analysis of the entire supply chain could prove whether the saving on transport and storage associated to decentralised scenarios could save environmental impact on the production of goods.

Acknowledgements

Authors acknowledge financial support received from the Centre for the Sustainable Energy Use in Food Chains - CSEF (EPSRC grant no. EP/K011820/1).

References

[1] Hu, S.J. (2013). "Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization". Procedia CIRP 7: 3–8.

[2] Srai, J.S., Kumar, M., Graham, G., Phillips, W., Tooze, J., Ford, S., Beecher, P., Raj, B., Gregory, M., Tiwari, M.K., Ravi, B., Neely, A., Shankar, R., Charnley, F., Tiwari, A. (2016). "Distributed manufacturing: scope, challenges and opportunities" *International Journal of Production Research* 54: 6917–6935.

[3] Garrehy, P. (2014) ."Centralised vs Decentralised Manufacturing". *Industry Today* 17: 28-39.

[4] Mourtzis, D & Doukas, M. (2012) ."Decentralized manufacturing systems review: challenges and outlook". *Logistic Research* 5: 113-121.

[5] Harrison, R.P., Rafiq, Q.A., Medcalf, N. (2018) ."Centralised versus decentralised manufacturing and the delivery of healthcare products: A United Kingdom exemplar" *Cytotherapy* 20:873-890.

[6] Angeles-Martinez, L., Theodoropoulos, C., Lopez-Quiroga, E., Fryer, P.J., Bakalis, S. (2018). "The Honeycomb model: A platform for systematic analysis of different manufacturing scenarios for fast-moving consumer goods" *Jounal of Cleaner Production* 193:315–326.

[7] Baldea, M., Edgar, T.F., Stanley, B.L., Kiss, A.A. (2017). "Modular Manufacturing Processes: Status, Challenges and Opportunities". *AIChE Journal* 63:4262–4272.

[8] Hannibal, M., Knight, G. (2018). "Additive manufacturing and the global factory: Disruptive technologies and the location of international business". *International Business Review* 27: 1116-1127.

[9] Department for Environment, Food & Rural Affairs-DEFRA. (2018). Food Statistics Pocket Box.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/608426/foodpocketbook-2016report-rev-12apr17.pdf

[10] Sellitto, M.A., Vial, L.A.M., Viegas, C.V. (2018). "Critical success factors in Short Food Supply Chains: Case studies with milk and dairy producers from Italy and Brazil.". *Journal of Cleaner Production* 170: 1361–1368.

[11] Sage, C. "Social embeddedness and relations of regard: alternative 'good food' networks in south-west Ireland." *Journal of Rural Studies* 10 (2003): 47–60.

[12] Matt, D.T., Rauch, E., Dallasega, P. (2015). "Trends towards Distributed Manufacturing Systems and modern forms for their design" *Procedia CIRP* 33: 185–190.

[13] Ruffo, M., Tuck, C., Hague, R. (2006). "Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes" *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture* 220: 1417–1427.

[14] Almena, A., Fryer, P.J., Bakalis, S., López-Quiroga, E. (2018). "Effect of decentralisation on food manufacturing: A modelling platform for technological, environmental and economic assessment at different manufacturing scales". *Article in Press*

[15] Almena, A., Goode, K.R., Fryer, P.J., Bakalis, S, López-Quiroga, E. (2018). "Optimising food dehydration processes: energy-efficient drum-dryer operation." *Energy Procedia*. Article in Press. ICSEF 2018.

[16] Purlis, E. (2011) ."Bread baking: Technological considerations based on process modelling and simulation." *Journal of Food Engineering* 103: 92–102.

[17] Carson, J.K., Willix, J., North, M.F. (2006). "Measurements of Heat Transfer Coefficients within Convection Ovens" *Journal of Food Engineering* 72: 293–301.

[18] Almena, A. & Martin, M. "Technoeconomic Analysis of the Production of Epichlorohydrin from Glycerol." *Industrial and Engineering Chemistry Research.* 55 (2016): 3226–3238.

[19] Government of United Kingdom (GovUK), 2017. Greenhouse gas reporting-Conversion factors 2017.
https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017 (accessed: 06/05/2017).