UNIVERSITY OF BIRMINGHAM

PH.D THESIS

MODELLING, SIMULATION AND EVALUATION OF CENTRALISED AND DECENTRALISED FOOD MANUFACTURING SCENARIOS

Alberto Almena-Ruiz

School of Chemical Engineering

College of Engineering and Physical Sciences

University of Birmingham

2020

Abstract

Current long-rigid centralized supply chains, responsible for high energy consumption and environmental impact, might become outdated in a near future. Many theoretical studies, predicting a shift on companies' strategical approach to the market based on scaling down and decentralization to reach mass differentiation, can be found in literature.

This work demonstrates that the shift on manufacturing paradigm can be studied as an engineering problem. Process system engineering methodology is implemented to develop a modelling tool, capable to generate trusted practical data for common and alternative manufacturing scale scenarios with increasing degree of decentralisation, i.e. Single plant production, Multiple plant production, Distributed Manufacturing, Food Incubator, and Home manufacturing. The tool is used to perform a techno-economic and environmental assessment for three food products of distinct characteristics, namely dry cereal porridge, sandwich bread and ice cream. The processing alternatives are first designed and studied separately for each food, to identify the benefits and tradeoffs associated to decentralised production methods. Variations on economic, social and environmental impact parameters along a wide range of production rates –e.g. 0.01 to 50,000 kg/h– are evaluated, and a UK demand framework is used to check the performance of the alternative production methods in a realistic scenario. A final comparison among the three items is performed to study how each scale differently functions for the production of each food studied.

The output of this research is to offer a robust tool that might assist companies in the complex decision between centralized or decentralized manufacturing systems for real market opportunities.

Acknowledgements

To become a PhD was never in my expectations. Not having embarked on this life experience would have been, however, one of the biggest mistakes in my life. I have not only grown professionally during my PhD, but it also gave me a priceless personal enrichment difficult to have been reached under other circumstances.

I would like to first thank Prof. Serafim Bakalis for giving me the opportunity to join the PhD programme in a so prestigious university. Also, to Prof. Peter Fryer, who took over the role as first supervisor and accepted me in his group. He has given me guidance, support and motivation during the last two years of the project, together with carrying out with the thesis correction. Many thanks to Dra. Estefanía López-Quiroga for her help during the whole PhD –and even before me arriving to the University– providing supervision, valuable feedback and becoming a model to follow. I could not forget Lynn Draper, her endless kindness and incomparable troubleshooting ability. She is part of this work as well. I would also like to acknowledge EPSRC for funding this PhD project.

Special thanks to my friends, the ones I made along this process, and the ones I left behind but never forgot me. I have never felt alone, even in the worst moments, and this is because of you guys. I love you all.

For the end, I keep the last lines to thank my parents Teresa and Aurelio, and my grandmother Ana. Without their unconditional love and education, I would have never been capable to reach any achievement in my life, including this PhD. I do not see myself able to correspond them to an equal extent. This thesis is dedicated to them.

Contents

Chapter 1: Introduction 1

1.1. Research context 2

1.2. Motivation, scope and objective of research 5

1.3. Thesis structure 8

Chapter 2: Literature Review 10

2.1. Introduction 11

2.2. Manufacturing 12

2.3. History of Manufacturing 13

2.3.1. Craft Production paradigm (Pre-Industrial Age – 1850) 15

2.3.2. Mass Production paradigm (1850 – 1980) 16

2.3.3. Lean Manufacturing (1980 – 2000) 18

2.3.4. Mass Customisation paradigm (2000s – 2010s) 19

2.4. Future of Manufacturing 20

2.4.1. Mass Individualisation 25

2.4.2. Distributed Manufacturing 26

2.5. Food Manufacturing 29

2.5.1. Evolution of Food processing 29

2.5.2. Food Process Engineering 33

2.5.3. Importance of Food Production Systems: Food Industry and Food Supply Chain 34

2.5.4. Centralised vs Decentralised Manufacturing in Food Industry 36

2.5.5. Distributed Manufacturing paradigms in Food Industry 39

2.6. Solving the scale down problem in manufacturing processes 43

2.7. Modelling and design of manufacturing processes 48

2.7.1. Process System Engineering 48

2.7.2. Mathematical modelling and optimisation of manufacturing processes 50

2.7.3. Optimisation in manufacturing systems 54

2.7.4. Mathematical principles used in data processing 56

2.8. Conclusions and main objective of this work 59

Chapter 3: Dry cereal baby porridge 61

3.1. Abstract 62

3.2. Introduction 63

3.3. Characterisation of different manufacturing scenarios 65

3.3.1. General description of the manufacture process 65

3.3.2. Production scenarios 70

3.4. Model description 71

3.4.1. Model assumptions 72

3.4.2. Mass and energy balances 75

3.4.3. Drying operations 76

3.4.4. Cost estimation 77

3.4.5. Net profit calculation 79

3.5. Results and discussion 80

3.5.1. Effect of the production scale on the operating cost 81

3.5.2. Data trend analysis on unit cost curves for each manufacturing scale 86

3.5.3. Effect of manufacturing scale on total capital 89

3.5.4. Case study: the UK dry baby food demand scenario 91

3.6. Overview: food manufacture trends and challenges 96

3.7. Conclusion 98

Chapter 4: Sandwich bread 100

4.1. Introduction 101

4.2. Product formulation 103

4.3. Design of the alternative manufacturing processes 104

4.3.1. Industrial bread making 104

4.3.2. Artisanal bread manufacturing 106

4.4. Model description 110

4.4.1. Model assumptions 110

4.4.2. Mass balance 113

4.4.3. Energy balance 114

4.4.4. Industrial process modelling and cost estimation 120

4.4.5. Artisan process modelling and cost estimation 122

4.4.6. Energy consumption and carbon footprint of bread making 124

4.5. Results and discussion 124

4.5.1. Operating cost evolution with throughput for bread making processes 125

4.5.2. Identification of the operational regions for the different bread making methods 129
4.5.3. Total capital and manpower needs in bread manufacture. 132
4.5.4. Case study: UK sandwich bread demand scenario 134
4.6. Conclusion 140
Chapter 5: Ice cream 142
5.1. Abstract 143
5.2. Introduction 145
5.3. Product formulation 147
5.4. Modelling of the thermal properties and rheology of ice cream 150
5.4.1. Ice fraction and freezing point depression curve 152
5.4.2. Specific heat 154
5.4.3. Density and volume fraction 154
5.4.4. Thermal conductivity 155
5.4.5. Viscosity of the mix 156
5.5. Different manufacturing processes design 158
5.5.1. Industrial manufacturing process 158
5.5.2. Artisan manufacturing processes 162
5.6. Model description 166
5.6.1. Model assumptions 167
5.6.2. Mass and energy balances 170
5.6.3. Industrial process modelling 171

5.6.4. Artisan process modelling 184

5.6.5. Energy consumption and carbon footprint of the processes 186

5.6.6. Economic evaluation 188

5.7. Results and discussion 189

5.7.1. Thermal properties behaviour for the different mix formulations 190

5.7.2. Operation cost of ice cream process at multiple manufacturing scenarios 192

5.7.3. Influence of the manufacturing scale on the total capital and labour 196

5.7.4. Data trend analysis of unit cost: identification of operational regions 198

5.7.5. Energy consumption of industrial and artisan manufacturing processes ... 203

5.7.6. Case study: Fulfilling the forecast expansion of the UK ice cream demand 206

5.8. Conclusion 211

Chapter 6: Comparison between the three products 214

6.1. Introduction 215

6.2. Cost correlations for unit cost and total capital 215

6.3. Characteristic points (HCS and PR) and operational regions 217

6.4. Economic and environmental impact assessment 221

6.4.1. Total capital per unit of production rate 222

6.4.2. Net profit per facility 224

6.4.3. Energy use and carbon footprint 225

6.5. Conclusion 229

Chapter 7: Conclusion and future work suggestions 231

7.1. Overview of methodology 232

7.2. Principal findings...233

7.3. Suggestions for future work 237

Bibliography 238

Appendix A: Supplementary material for Chapter 3 269

Appendix B: Energy efficient drum dryer operation..........................289

Appendix C: Supplementary material for Chapter 4 305

Appendix D: Supplementary material for Chapter 5 309

List of Figures

Figure 1.1. Transportation energy consumption and projections….……………………….3

Figure 1.2. Population growth by region: historical population data and projections ….……………………………………………………………...4

Figure 2.1. What is our idea of manufacturing? ………………………………………….12

Figure 2.2. Evolution of the manufacturing paradigms…………………………………..14

Figure 2.3. Competitiveness strategies followed by the different manufacturing paradigms……………………………………………………………………17

Figure 2.4. Evolution of the number of published documents regarding 'Sustainable Manufacturing' (Scopus database)…………………………....21

Figure 2.5. Characterization of the different existing manufacturing paradigms through history…………………………………………………………23

Figure 2.6. (a) Centralised Manufacturing (scenario A) vs. (b) Distributed Manufacturing (scenario B)……………………………………………….27

Figure 2.7. Evolution of food processing………………………………………………...30

Figure 2.8. Venn diagram showing the interdisciplinary nature of food process engineering…………………………………………………………………..33

Figure 2.9. Different stages comprising the food supply chain………………………….36

Figure 2.10. Food product supply chain. (a) Centralised Manufacturing vs. (b) Distributed Manufacturing………………………………………….....38

Figure 2.11. Total operating cost in a manufacturing plant, from non-production to maximum plant capacity…………………………………………………...45

Figure 2.12. Operating cost per unit of product behaviour in manufacturing……………45

Figure 2.13. Application of the six tenth rule to an equipment that initially cost 14,000 $ for producing 350 kg/h..…………………………………………46

Figure 2.14. Basic stages in the modelling of manufacturing processes…………………51

Figure 3.1. (a) Baby food plant production and (b) Artisanal manufacture flow chart……67

Figure 3.2. Schematics representing the production methods and scales considered in this work……………………………………………………………..70

Figure 3.3. Flow diagram representing the sequential process to build and solve the modelling of cereal porridge manufacturing scales…………………………72

Figure 3.4. Variation of the unitary cost with porridge throughput for different production scales………………………………………………………….82

Figure 3.5. Example of how the different operation regions for a manufacturing scale are identified: Graphs show (a) DM low Management and (b) Single Plant scenarios……………………………………………………87

Figure 3.6. (a) Total capital and (b) Manpower required for each production scale at different final product´s production rates…………………………...90

Figure 3.7. Total capital (a) and unitary operating cost (b) for HM, FI, DM, SP and MP production scenarios under UK dry baby food demand (418 kg/h)…………92

Figure 4.1. Industrial flow chart for bread manufacturing in a processing plant……….105

Figure 4.2. Artisan bread manufacturing flow chart for HM and FI……………………..107

Figure 4.3. Industrial flow chart for bread manufacturing in a processing plant……….108

Figure 4.4. Flow diagram depicting the sequential process to build and solve the modelling of all industrial and artisanal bread manufacturing scales………111

Figure 4.5. Heat transfer to the bread loaf in the oven…………………………………..116

Figure 4.6. Variation of the unit cost ($/kg) for different manufacturing scales in the production of 800g sandwich bread loaves…………………………127

Figure 4.7. Identification of the three different operation regions defined in this work for bread manufacturing carried out in (a) DM –franchise or low management model– and (b) SP manufacturing…………………………...129

Figure 4.8. Total Capital (a) and Manpower (b) results for the four manufacturing scales in bread making…………………………………………………..133

Figure 4.9. Variation of the unit cost ($/loaf) for industrial manufacturing organised in multiple processing plants……………………………………………135

Figure 5.0. Range of applications for the different ice cream manufacturing scales……144

Figure 5.1. (a) Schematic representation and (b) Microscopic observation of the ice cream microstructure…………………………………………………...151

Figure 5.2. Ice cream plant production flow sheet depicting all the steps of the industrial process…………………………………………………………...160

Figure 5.3. Artisanal manufacture flow chart for (a) Distributed Manufacturing and (b) Food Incubator and Home manufacturing…………………………165

Figure 5.4. Flow diagram representing the sequential process to build and solve the modelling of (a) industrial –batch or continuous–and (b) artisanal ice cream manufacturing scales..……………………………..166

Figure 5.5. Batch pasteuriser. Jacketed stirred vessel with internal coil for heat transfer…………………………………………………………………...173

Figure 5.6. Heat transfer installation design for a bath pasteuriser……………………..175

Figure 5.7. Continuous pasteuriser. Plate heat exchanger device with the different sections: cooling, regeneration and heating………………………………..177

Figure 5.8. PHE design routine…………………………………………………………178

Figure 5.9. Representation of a SSHE used for ice cream dynamic freezing…………...179

Figure 5.10. Scheme representing the computational routine for the design of the continuous freezer (SSHE)…………………………………………………183

Figure 5.11. Thermal properties of standard (S – orange) and premium (P – blue) ice cream formulations: (a) Enthalpy (b) Ice weight fraction curve (c) Thermal conductivity and (d) Density………………………………...191

Figure 5.12. Variation of the unit cost ($/kg) for different manufacturing scales in the production of premium ice cream sold in 500 ml units……………….194

Figure 5.13. Variation of the unit cost ($/kg) for different manufacturing scales in the production of (a) Premium (HQ) ice cream sold in 150ml units and (b) Standard ice cream sold in 1000ml units…………………………...195

Figure 5.14. Total Capital (a) and Manpower (b) results for the four manufacturing scales…………………………………………………………………...197

Figure 5.15. Identification of the three different operation regions defined in this work for industrial ice cream manufacturing carried out in (a) Single plant manufacturing and (b) Two Plants manufacturing……………….....199

Figure 5.16. Identification of the three different operation regions defined in this work for artisan manufacturing scenarios: HM, FI and DM (franchise and corporation management models)……………………………………202

Figure 5.17. Energy consumption for (a) Single plant manufacturing and (b) Four plants manufacturing…………………………………………………...203

Figure 5.18. Energy consumption for HM, FI and DM…………………………………205

Figure 5.19. Analysis of all manufacturing scales in a UK demand scenario: (a) Cost per kg of ice cream (b) Total capital required…………………...207

Figure 5.20. Net profit per facility for the artisan manufacturing scales……………….209

Figure 5.21. Analysis of all manufacturing scales in a UK demand scenario: (a) Number of facilities and manpower –logarithmic y-axis– (b) Total energy consumed per kg of ice cream manufactured…………...210

Figure. 6.1. Characteristic points of production cost curves for all the scales. Graphs on the left represent high change on slope (HCS) points, while graphs on the right represents plateau reaching (PR) points for each manufacturing scale assessed…………………………………..219

Figure. 6.2. Total capital per unit of throughput. The five manufacturing scales are applied and compared for the three food products evaluated in a UK demand alike scenario…………………………………………………………..222

Figure. 6.3. Net profit per facility comparison of artisan scales profitability for the three food products evaluated in a UK demand scenario………………….225

Figure. 6.4. Three foods energy use comparison……………………………………….228

Figure. 6.5. Three foods carbon footprint comparison………………………………….228

List of Tables

Table 3.1. Unit operations, operating conditions and equipment used for industrial and artisanal dry cereal porridge manufacturing processes…………………..69

Table 3.2. Crossover points from *Fig.3.4* for each manufacturing scale, including uncertainties: lower bound (lb) and higher bound (hb)…………....85

Table 3.3. High change on slope (HCS) and plateau reaching (PR) points for each porridge manufacturing scale…………………………………………........88

Table 3.4. Carbon Footprint of HM, FI, DM, SP and MP (two plants) at the manufacturing stage for cereal porridge…………………………………...95

Table 4.1. Formulation of dough for three different recipes: conventional bread, part baked and frozen bread, and French bread……………………………..103

Table 4.2. List of the unit operations, operating conditions and equipment comprising a continuous industrial processing line for bread making…………………..106

Table 4.3. List of unit operations, operating conditions and equipment used for the three manufacturing scales involving an artisanal manufacturing process (batch operation)……………………………………………………109

Table 4.4. Crossover points of SP and MP and the artisan bread manufacturing methods cost curves obtained from *Figure 4.5*……………………………………….128

Table 4.5. Linear fitting for all the operational region –unfeasible, transition and plateau– in which each bread manufacturing scale can perform……………131

Table 4.6. Economy estimation, energy demand and carbon load results for bread making in a demand scenario similar to UK sandwich bread national demand……………………………………………………………..138

Table 5.1. Content range and functions of components for plain ice cream mix formulations……………………………………………………………………148

Table 5.2. Standard ice cream mix formulation, taken from the ingredient list of Carte D'Or®……………………………………………………………………149

Table 5.3. Premium ice cream mix formulation, taken from the ingredient list of Ben & Jerry's Chunky Monkey®…………………………………………………150

Table 5.4. Unit operations, operating conditions and equipment used for industrial (continuous and batch) ice cream manufacturing processes………………...159

Table 5.5. Unit operations and equipment used for artisan (batch) ice cream manufacturing processes…………………………………………………………164

Table 5.6. High change on slope (HCS) and plateau reaching (PR) points, defined in section 5.7.4, for the manufacturing of premium ice cream sold in 500ml tubs…………………………………………………………………...201

Table 6.1. Unit cost and Total Capital fit parameters for all the manufacturing scales when processing cereal porridge, sliced bread and ice cream………..216

Nomenclature

Chapter 2: Literature Review.

Lowercase

f	Evaluated function	x_i	Signal data element of vector $\bar{x}$
h	Grid spacing	y_i	Dependent variable element
k	Partitioning element (instant)	$\hat{y}_i$	Predicted dependent variable element
n	Cost exponent / number of elements	var	Variance
r_i	Residual element		

Uppercase

A	Equipment Design Variable	LP	Lean Production
AFN	Alternative Food Network	MC	Mass Customisation
AM	Additive Manufacturing	MI	Mass Individualisation
AP	Artisan Production	MM	Modular Manufacturing
C	Cost of equipment / Component	MP	Mass Production
CMS	Centralised Manufacturing Systems	OAP	Open-platform architecture products
CP	Craft Production	P	Products
DM	Distributed Manufacturing	PSE	Process System Engineering
DMS	Distributed Manufacturing Systems	R	Least-Squares objective function
FDM	Finite difference method	RMS	Re-Distributed Manufacturing Systems
GHG	Greenhouse gases	S	Sample corrected sum of squares
GVA	Gross Value Added	SCM	Supply Chain Management
ICT	Information and Communication Technologies	$SFSC$	Short Food Supply Chain
IoT	Internet of the Things	SQP	Sequential Quadratic Programming
J	Cost function		

Greek Symbols

θ_i	Parameter element of vector $\bar{\theta}$	χ	Empirical estimate
μ	Mean	Δ	Deviation measurement

Chapter 3: Cereal Porridge

Lowercase

c_p	heat capacity (kJ kg^{-1} ˚C^{-1})	ICT	Information and Communication
lb	lower boundary	q	annual product sold (kg/year)
p	price ($)	ub	upper boundary
		x	mass fraction (kg kg^{-1})

Uppercase

$2P$	Two plants		
AFN	Alternative Food Network	$\dot{M}$	Mass flux (kg h^{-1})
C	Annual operating cost ($ year^{-1})	$MM\$$	Millions of Dollars
CL	Carbon load (kg CO_2e kg^{-1})	MP	Multi-Plant production
CM	Centralised manufacturing	N	number of
DM	Distributed manufacturing	PR	Plateau reaching
FI	Food Incubator	$SFSC$	Short Food Supply Chain
GHG	Greenhouse gases	SP	Single Plant production
H	enthalpy (kJ kg^{-1})	T_{corp}	Corporation tax reduction
HCS	High change on slope	T	temperature (˚C)
HM	Home manufacturing	VAT	value added tax

Subscripts

bf	baby food	J	Inlet stream
elect	eelectricity	K	outlet stream
evap	evaporation	plants	industrial production sites
fac	facility	prod	product
i	component index		

Greek Symbols

Δ	gradient	Π	Net profit

Chapter 4: Sandwich Bread

Lowercase

c_p	heat capacity (kJ kg^{-1} °C^{-1})	$low\ M.$	low management cost assumptions
h	enthalpy (kJ kg^{-1})	t	time (s)
h_a	apparent heat transfer coefficient (W m^{-2} K)	x	mass fraction (kg kg^{-1})
$high\ M.$	high management cost assumptions	x_{loss}	mass loss ratio

Uppercase

$2P$	Two plants	MP	Multi-Plant production
A	Surface (m^2)	$PBFB$	Part baked and frozen bread
DM	Distributed manufacturing	PR	Plateau reaching
F_{waste}	Waste factor	Q	heat (J)
FI	Food Incubator	SP	Single Plant production
HCS	High change on slope	T	Temperature (°C)
HM	Home manufacturing	U	global heat transfer coefficient (W m^{-2} K)
LHV	low heating value (J m^{-3})	X_{crust}	Ratio crust-crumb
M	Mass (kg)	X_{steam}	Steam/dough mass ratio

Subscripts

bake	baking	max	maximum
gel	gelatinisation	proof	proofing
i	component index	prov	proving
j	fuel index	raw	uncooked dough property

Greek Symbols

η	yield	Δ	gradient
λ	enthalpy of vaporisation (water)		

Chapter 5: Ice Cream

Lowercase

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

Uppercase

A	surface (m^2)	$\dot{M}$	production rate (kg h^{-1})
C	circumference (m)	N_P	Power number
COP	coefficient of performance for a refrigerant	Nu	Nusselt number
D	diameter (m)	OC	operation Cost ($ $year^{-1}$)
F	experimental factor (dimensionless)	Ov	overrun percentage
FPF	freezing point factor	P	Power/Shaft work (W)
GWP	global warming potential (kgCO_2e kg^{-1})	Pr	Prandtl number
G	mass flow per surface unit (kg m^{-2} s^{-1})	Q	heat (J)
$HTST$	High temperature short time	$\dot{Q}$	heat flow (J s^{-1})
IPS	Iron pipe size (in)	Re	Reynolds number
K	consistency index (Pa.s^n)	SE	equivalent of sucrose (kg mol^{-1})
L	latent heat (kJ kg^{-1})	T	temperature (°C)
LHV	low heating value (kJ m^{-3})	TS	total solids content (%)
$LTLT$	low temperature low time	U	global heat transfer coefficient (W m^{-2} K)
M	molar mass (g mol^{-1})	V	volume (m^3)
N	number of	$\dot{V}$	volume flow (m^3 s^{-1})

Subscripts

0	starting point	lb	lower bound
app	apparent	lm	logarithmic mean
b	freezing barrel	mix	pre-frozen mix
b-d	batches in a daily base	msnf	milk solids non fat

bf	baffle	o	outer
c	cylinder	out	outlet
cond	condensate/condenser	p	plate
cont	continuous phase	p-d	actual productive time in a daily base
corp	corporation	past	pasteurisation
e	external	PHE	plate heat exchanger
evap	evaporator	pt	port
f	fusion	raw	pre-pasteurised mix
fd	freezing point depression	ref	refrigerant
hom	homogenised	reg	regeneration
i	inner	ss	stainless steel
ic	ice cream	st	solute
ice	ice phase	sv	solvent
ii, jj	iteration step	t	turbine
IF	initial freezing	u	useful
im	impeller	ub	upper bound
in	inlet	v	vessel
j	individual food component	VAT	value added tax
jk	jacket	w	water
k	dissolved substance	wall	property by the wall

Greek Symbols

$\dot{\gamma}$	shear rate (s^{-1})	μ	viscosity (Pa s)
Γ_h	horizontal tube loading ($kg\ m^{-1}\ s^{-1}$)	Π_{fac}	net profit per facility ($ $facility^{-1}$ $year^{-1}$)
δ	thickness (m)	ρ	density ($kg\ m^{-3}$)
ε	volume fraction	τ	tax percentage (%)
η	yield	χ	conservation property
λ	thermal conductivity ($W\ m^{-1}\ k^{-1}$)	ω	rotational speed (s^{-1})

Chapter 6: Comparison among the three products

Lowercase

a, b, c	power fit parameters	q	production rate (kg h^{-1})
d, e	linear fit parameters		

Uppercase

$2P$	Two plants	I	Capital cost (M$)
C'_{prod}	Unit cost ($ kg^{-1})	MP	Multi-Plant production
DM	Distributed manufacturing	PR	Plateau reaching
FI	Food Incubator	R^2	coefficient of determination
HCS	High change on slope	SP	Single Plant production
HM	Home manufacturing		

Chapter 7: Conclusion and future work suggestions

Uppercase

$2P$	Two plants	LCA	Life cycle analysis
DM	Distributed manufacturing	MP	Multi-Plant production
FI	Food Incubator	SP	Single Plant production
HM	Home manufacturing		

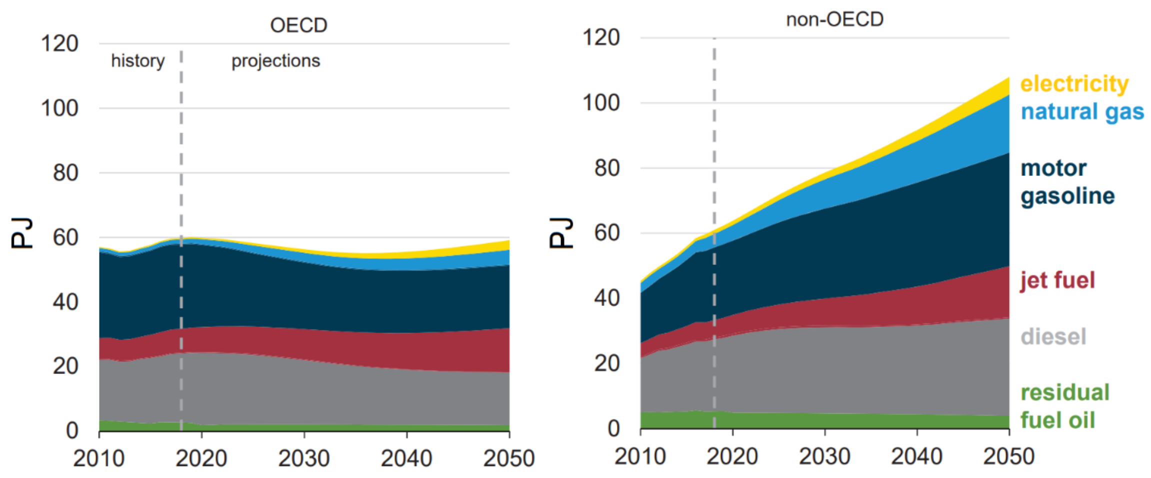
Chapter 1

Introduction

1.1. Research context

Sustainability has become a critical factor in the design of food manufacture systems (Govindan, 2018; Rohmer et al., 2019), as the need to mitigate the environmental impacts of food processing –one of the major responsible for fossil fuels consumption and GHG emissions (FAO 2017; Department for Business, Energy and Industrial Strategy, 2018 & 2019; EIA 2019)– grows more and more urgent.

The food value chain consumes approximately 200 EJ per year worldwide (Ladha-Sabur et al., 2019). In high gross domestic product (GDP) countries, it is estimated that 45 % of the energy used by the food system is related to food processing and distribution activities, and 30 % in retail preparation and cooking. This cooking share is even greater for low-GDP countries (Sims et al., 2015). Nowadays, the conventional food system mostly comprises large-scale and mechanised energy-intensive manufacturing processes (Mundler and Criner, 2016). Despite renewable energies have shown the fastest rate of growth, fossil fuels remain being the most-used energy sources for this industry (EIA, 2019). With respect to food transportation, Fig.1.1 shows how oil products are also the primary sources of energy consumption. Several studies have reported a worldwide increase on both volume and distance travelled by food during the last decades (Grebritus et al., 2013; López et al., 2015; Duarte et al., 2019). For example, the volume of food transported by heavy goods vehicles has increased by 23%, and food miles–i.e. the distance from farm to the fork of the final consumer (Pullman and Wikoff, 2017)– has rocketed in the UK for the last 40 years (Department for transport, 2018; Ladha-Sabur et al., 2019). The forecast predicts that the use of liquid fuel in transportation will increase and remain predominant for the year 2050. The greatest rise is expected for those regions that show the fastest growth in gross domestic product, i.e. non-OECD countries in Asia and Africa (EIA, 2019).



(a) (b)

Figure 1.1. Transportation energy consumption and projections for (a) Organisation for Economic Co-operation and Development (OECD) member countries and (b) non-OECD member countries (figure taken from EIA, 2019). Transportation sector is mainly based on liquid fuel consumption. Projections show a greater increase on energy consumption for developing countries (i.e. most of non-OECD countries).

Current practices in food manufacture are therefore considered unsustainable (FAO, 2017; EEA, 2020). The energy intensity identified in both processing and transportation, together with the wide use of fossil fuels as energy source, is linked to large levels of greenhouse gas emissions (GHG). Food production is responsible for 26% world's greenhouse gas emissions (Ritchie and Roser, 2020). A great contribution to climate change is thus accounted, which would have a negative impact on future global food security related to food supply, food quality and food access and utilization (Porter et al., 2014).

The concern for finding more sustainable food value chains is endorsed by the demanding increase on food supply. Greater food production will be necessary for the near future due to the forecasted growth in population (see Fig 1.2). It is estimated that the capacity of the global food system must increase by a 50% for the year 2030 (Tassou et al., 2014). This scenario makes essential to keep implementing the current global food system for the stability of food security and, thus, to keep depleting chronic hunger (Kamonpatana, 2019).

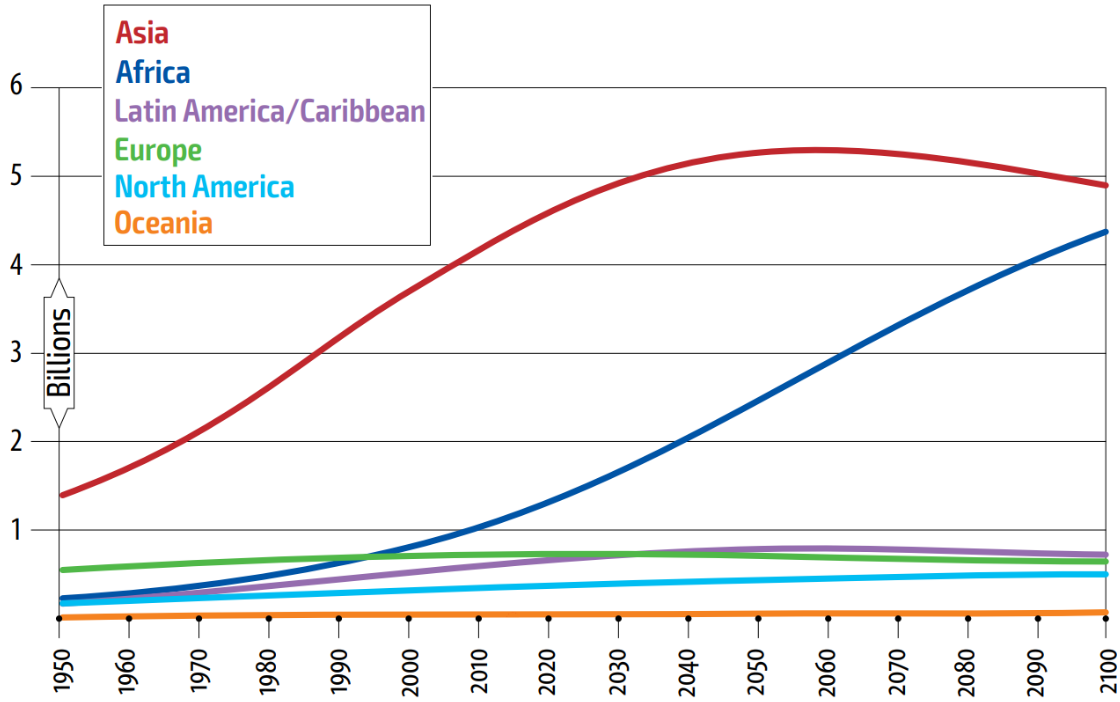


Figure 1.2. Population growth by region: historical population data and projections (figure taken from FAO, 2017).

In this framework, the study of alternative food value chains that decrease food miles and involve sustainable manufacturing methods for food industry is required. Local food supply chains have been studied as an alternative to conventional food systems that might encompass savings in environmental impact, waste reduction, generate more employment and deliver food considered healthier than industrial food (Coley et al., 2009; Mundler and Criner, 2016; Pullman and Wikoff, 2017, López-Avilés et al., 2019), while keeping economic competitiveness (Akbar and Irohara, 2018)..In this context, alternative production scenarios based on emerging "on-demand" and "sharing" models, together with distributed manufacture methods, could enhance sustainability across the food supply chain (Kumar et al., 2019). Such alternatives are based on a restructuring of production into decentralised small-scale facilities (Sellitto et al., 2018; Jarosz, 2018; Angeles-Martinez et al., 2018), which shortens distances to consumers –thus decreasing energy use and emissions linked to product transportation and storage (Srai et al., 2016a)– and/or involves more sustainable and ethical practices into manufacturing processes (Cottee, 2014; Rauch et al., 2017). A higher engagement between local producers and consumers would be necessary (Mundler and Criner, 2016). All these changes are facilitated by (i) the increasing digitalisation of the food sector, which minimises logistics cost (Kagermann, 2015; Maslarić et al., 2016) (ii) the growth of ICT (i.e. Information and Communications Technologies), which speeds up interaction between manufacturers and consumers (Miranda et al., 2019), and (iii) new manufacturing technologies, such as additive (Freeman and McMahon, 2019) and modular manufacturing (Baldea et al., 2017), which might be better suited for decentralised structures.

1.2. Motivation, scope and objective of research

Most of the up-to-date research found in literature addresses how decentralised manufacturing scenarios could work in a theoretical way. There is a lack of empirical work and systematic approaches in local food processing systems (Roos et al., 2016). To fill this gap, this thesis uses process system engineering methodologies to present a model-based techno-economic and environmental assessment that shows how alternative decentralised scenarios perform compared to centralised manufacture at different scales of production. The objective is therefore not only to describe different food manufacturing systems, but also to provide a practical and versatile mathematical tool that generates trusted data (process design, economics and environmental impact) and enable the analysis of those alternative scenarios and their potential performance.

The scope of this work is focused only on the manufacturing stage of the supply chain. A basis to incorporate the remaining steps of the whole food value chain has been therefore settled for future work. A modelling tool has been developed to (i) define artisan and industrial processing methods (i.e. unit operations involved, as well as corresponding energy and material balances), (ii) estimate production costs and (iii) evaluate environmental impacts for a wide range of production scales. Different levels of complexity (e.g. number of unit operations or production lines) and uncertainty sources (e.g. fluctuation of raw materials and/or energy prices) were included in the model. The novelty of this approach is two-fold:

(a) It creates a virtual design of a processing facility (with size ranging from an industrial plant to home-made scale) for three different food products. This connects energy and mass flows in processing flowsheets and uses ad-hoc designs for each unit operation – i.e. industrial equipment is selected and sized according to production rates, operating conditions and product recipe to satisfy energy and material balances of each processing step.

(b) It provides a scenario-based, flexible and robust tool that can support decision-making and strategic planning for food processing at all production scales. This tool has the potential for helping food manufacturers and stakeholders to assess the economic and environmental performance of their processes, step by step, setting the basis for more sustainable food processing methods.

To prove the versatility of the developed methodology, three food exemplars, characterised by dissimilar features, have been studied: dry cereal porridge, sliced bread and ice cream. *Cereal porridge* is a representative of dry food manufacturing, which typically encompasses energy-intensive processes whose heat demand is directly related to the water removal needed (Ladha-Sabur et al., 2019). Cereal porridge suitable for baby feeding, which comprises a more complex manufacturing process (a starch gelatinisation step is included to ease digestion) is the item chosen here. The resulting dry products show long shelf life (low water activity) and a reduced specific volume that minimises storage and transportation costs. This example therefore represents the type of food that may take the least advantages from a decentralised production. On the other hand, *bread* is a semi-perishable food that is best consumed when fresh (Dal Bello et al., 2007). Manufacturing methods that involve short supply chains and therefore delivery times might solve the economic losses caused from bread staling, i.e. a spoiling happening during storage (Gray and Bemiller, 2003). The last food product, i.e. ice cream, is an exemplar of an energy-intensive supply chain. Ice cream is a frozen product that must be kept below -15˚C, so significant costs and energy consumptions –and therefore carbon emissions– are caused from transportation and storage (Konstantas et al., 2019). A decentralised manufacturing model might help to minimise mileage and storage times, and therefore incur in economic and environmental impact savings.

1.3. Thesis structure

The structure of the thesis is briefly described below.

Chapter 2 will provide a background to the developed research and an introduction to the three main results sections. An overview of the evolution of manufacturing paradigms is first realised to contextualise and identify the current shifting scenario. The existing alternatives in manufacturing models that compete to satisfy the new market challenges, aimed at sustainable and flexible production, are explained. Distributed manufacturing, based on scaling down and localised production, is assessed here as an alternative to the existing centralised processes that might fulfil those demands. The reasons for choosing the food processing sector and how distributed manufacturing can be applied are discussed. The chapter closes explaining how process system engineering methods can be applied to fill the existing lack of systematic approaches in local food processing systems.

Chapter 3 contains work published in Sustainable Production and Consumption (Almena et al., 2019a). The basis of the developed methodology is described and applied to the manufacturing of a dry food item, i.e. cereal porridge. Five processing scales for food production, characterised by different degrees of decentralisation from domestic production to industrial plant manufacturing, are modelled and simulated. Results generated by the modelling platform are used to compare all scales in economic, social and environmental terms.

Chapter 4 then applies the implemented methodology to bread making, a second food with different features. The same concepts developed in in chapter 3 are adapted to bread manufacturing to see the effect of decentralisation in a low value-added item that requires to be sold fresh.

Chapter 5 contains work published in Journal of Food Engineering (Almena et al., 2020). It encompasses the production of a much more complex food such as ice cream. To the best of our knowledge, this is the first published work modelling ice cream processing, together with profitability and environmental evaluation, thus enhancing the novelty of the contribution. Multiple production scales analysis is also performed for this frozen item.

Chapter 6 compares the three foods previously studied to see how decentralised manufacturing affects different products. As an additional outcome of the work, cost correlations have been developed to predict production cost and total capital invested for each manufacturing scale and food processed.

Chapter 7 comprises the final conclusions resulting from the presented research work, together with some recommendations for work in the future.

As end pages, several Appendixes support the information enclosed in the main text. The list of references is also included at the end of this thesis.

Chapter 2

Literature Review

2.1. Introduction

In this chapter, the reader will be firstly persuaded to abandon the commonly understood link between manufacturing and large-scale factory production. A brief travel through the history of manufacturing will help to understand the changing nature of the prevailing paradigm, constantly trying to satisfy the particularities of the demand at each time. The current shift in the manufacturing paradigm is noticed later, and the features that the new scheme must fulfil are pointed out. An existing debate between centralised and decentralised manufacturing is then identified. Subsequently, food manufacturing is selected as the industrial sector to address in this work. Its inherent importance in economy, society and environmental impact, together with the possibility –unlike other goods– for food to be produced at home, makes this item preferable for this study. The enablers for a successful decentralised manufacturing model applied to the food industry are carefully discussed, and the hurdles that it must overcome are indicated.

During the literature review, the appreciated lack of empirical and numerical work assessing this new approach led to propose a modelling platform to compare centralised and decentralised manufacturing, thus helping companies with this complex decision. A review of the process system engineering methodology, proven to be successful in other disciplines such as chemical engineering, is carried out to later suggest that these methods might be worth applying to food processing. Finally, the sequential procedure for the modelling of manufacturing processes is described, and the mathematical principles used for the analysis of results are compiled.

2.2. Manufacturing

Manufacturing is one of the central enhancers of economic growth for developed and developing countries (Gabriel and Santana-Ribeiro, 2019). In the EU in 2016, the manufacturing sector was the second non-financial business in terms of employment, with 2.1 million enterprises that involve 30.4 million employees. It also made the largest contribution to the non-financial business economy by generating € 1,912 billion (26.6 % of total) within the EU-28 (Eurostat, 2019).

Manufacturing processes also have a high impact –positive and negative– on the society and environment. Their primary role is to supply goods, services and systems that society needs; employment linked to manufacturing services supports numerous families and individual economies. On the other hand, it predominantly uses non-renewable energy, produces a high volume of greenhouse gas emissions, and has contributed to resource depletion (Sutherland et al., 2016).

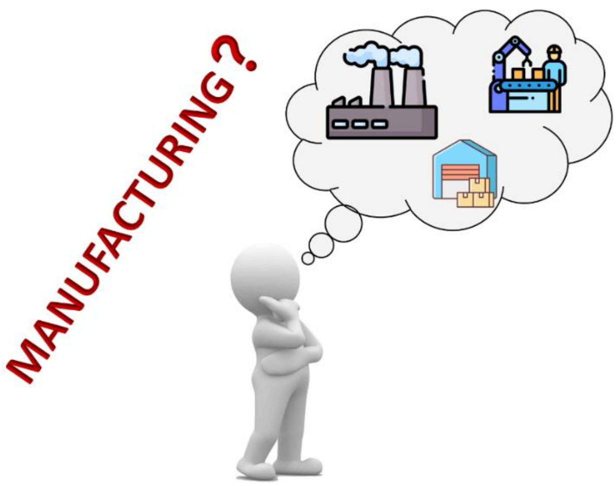


Figure 2.1. What is our idea of 'manufacturing'? Large scale and factories are commonly associated to the idea of manufacturing systems nowadays.

Manufacturing is a very common concept. When a simple google search for a technical definition of the word '***manufacturing'*** is done, the first returning result is "the process of converting raw materials, components, or parts into finished goods that meet a customer's expectations or specifications, commonly employing a man-machine setup with division of labour in a large scale production" (Business Dictionary, 2019). Immediately below, a second link conveys the idea of manufacturing as "the process or business of producing goods in large numbers in factories" (Market Business News, 2019). Both definitions capture the existing close bond between manufacturing and ***large-scale production***, almost an axiom in the present times.

As depicted in Fig. 2.1., it is very likely that, following this logic, the first thinking coming to our minds when we are asked about manufacturing is "***big factories***". However, this reasoning has not always been that intuitive. The origin of the word "manufacture" is the Latin compound term *manufactura*, meaning 'made by hand' (Skeat, 1882). The basis is thus much older than the existence of factories and it is most certainly not related to mass production. It does not seem unreasonable to suggest that, in a near future, product manufacturing can shift once again and not keep being mainly developed in large-scale factories.

2.3. History of Manufacturing

The manufacturing paradigm, i.e. the prevailing production method at each time, has been involved in key transformations during the last two centuries. Here, the evolution of the governing manufacturing models, enhanced by the social and economic needs in different historical periods, and enabled by the contemporary existing technology, is briefly reviewed. In *Fig.2.2*, a scheme of the evolution of the prevailing manufacturing regimes is shown.

Mankind, throughout its history, has been involved in the continuous process of using natural resources and transforming them into useable products, seeking to improve quality of life. Initially, human beings used to fabricate items for self-consumption, using muscle strength and primitive tools. Later, the emerging family system and congregation into communities required an increase of productivity, so muscle power was progressively replaced by first animal power, and later natural power –i.e. flowing water and wind (Hazarika et al., 2019). With the growth of civilization, the division of labour was established. The fabrication of goods became not only a self-sufficiency activity, but also started gaining commercial importance.

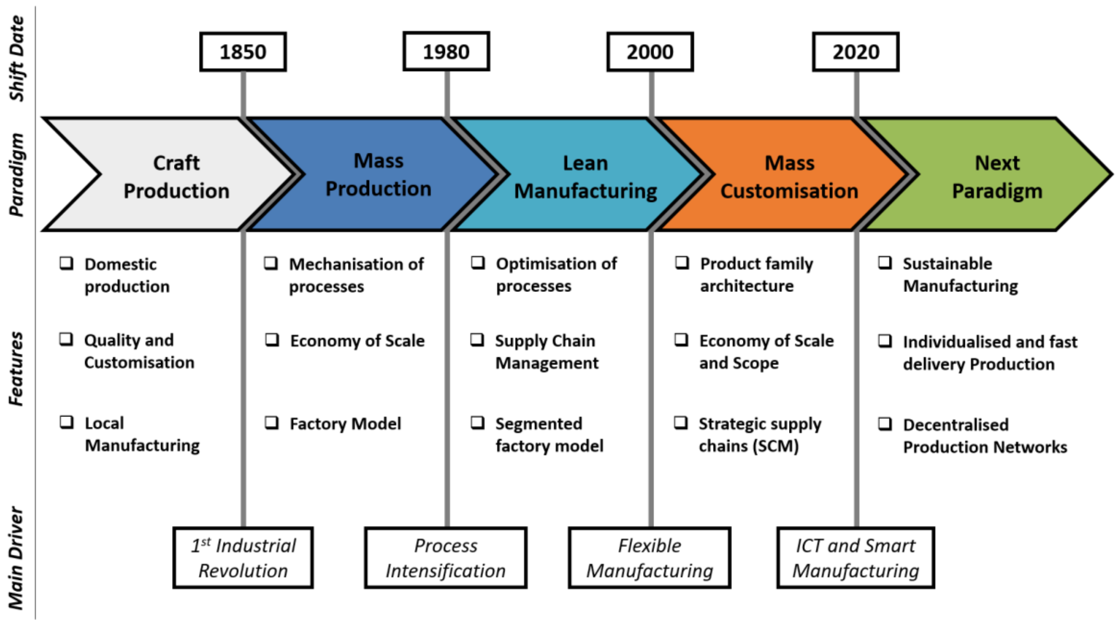


Figure 2.2. Evolution of the manufacturing paradigms. The main features of each method are shown, together with the principal driver and the approximate date of each shift.

2.3.1. Craft Production paradigm (Pre-Industrial Age – 1850)

At the end of the Pre-Industrial Age (ca. 1760), in the most advanced economies in the world manufacturing was based on domestic production in small family workshops by craftsmen and labourers-apprentices. Products were developed using craft methods, combining high skills with hand tools and simple equipment (Koren, 2010). The artisan manufacturers were spread across communities (with those most skilled based in cities), their target market was the local neighbourhood, so local demand was satisfied (Cipolla, 2013). Only wealthy merchants were able to perform retail and long distance (even international) trades. This first manufacturing paradigm is known as 'Craft Production'.

As a result of the use of traditional methods, small scale production and localisation, the provided final good was individually designed –comprising regional characteristics– within a short delivery time. The commercial strategy followed by the manufacturers to attract customers focused on providing high quality and customised products (see *Fig.2.3*). Craft Production (CP) system was feasible as it required low investment; the householder provided the little capital needed and relied on cheap labour, while a capitalist purchased the raw materials and negotiated the selling of the final product (Stearns, 2007). The expansion and spread of manufacturing productivity were determined by the increasing available labour, and the stability of the model did not incentivise technology development.

However, in the late 1700s, improvements in food production, such as the spread of potato cultivation and nitrogen-fixing crops in Europe, promoted growth in population and hence available workforce. New consumer interests appeared, fuelling the creation of new markets and increasing the activity of commercial economy (Stearns, 2007). These changes, together with multiple breakthroughs in science and technology, sparked the First Industrial Revolution.

2.3.2. Mass Production paradigm (1850 – 1980)

The First Industrial Revolution is the transition phase to new manufacturing processes, that took place in Europe and US between 1760 and 1840. It enabled the combination of machinery with sources of power that led to a factory system (Mantoux, 2013). The new machines required a factory organization model, due to barriers in power transmission. Workers were relocated under supervision, close to the equipment comprising the production line (Schmenner, 2001). Throughput per worker soared, along with a fall in prices that increased sales and allowed market expansion and exports. Capital was then required for starting a business, creating barriers for new companies to enter the market. The manufacturing paradigm shifted from Craft to '***Mass Production'***. In Britain, water-powered loom and cotton spinning-machinery in textiles, or steam powered machines in metallurgy, are exemplars of the mechanisation of manufacturing lines. This trend continued in the Second Industrial Revolution (ca.1870 – 1910) with the development of steel, petroleum and electricity industries.

A key enabler for the success of Mass Production (MP) was the concept of interchangeable parts. The new large-scale mechanized production lines were based on very specialized machines, manufacturing identical interchangeable parts that were assembled at the factory in a final stage, requiring low-skilled, and hence, cheap labour (Bianchi and Labory, 2019). That fact led to a standardisation of the final product and achieved a slump in prices. Competitivity in the market was not just in making the highest quality on the final product, but to lower the cost and production time (see *Fig.2.3*). The ***economy of scale*** rose as the tenet to follow for developing a more capital-efficient process and an improvement of the resource deployment. Taking advantage of this economy of scale –the cost per unit decreases as more units are purchased (Chen, 1998)– production was gradually clustered in a smaller number of factories with increasing size and production rate. Therefore, the inherent decentralisation of CP changed into '***centralised manufacturing***'. The Ford Motor Company, starting up their breakthrough assembly line in 1913, was one of the greatest exponents and pioneers of MP (Hounshell, 1985). Conversely, despite the fact that CP was no longer the predominant manufacturing model, it survived as specialised product manufacturing that required little capital for starting a business (Koren, 2010).

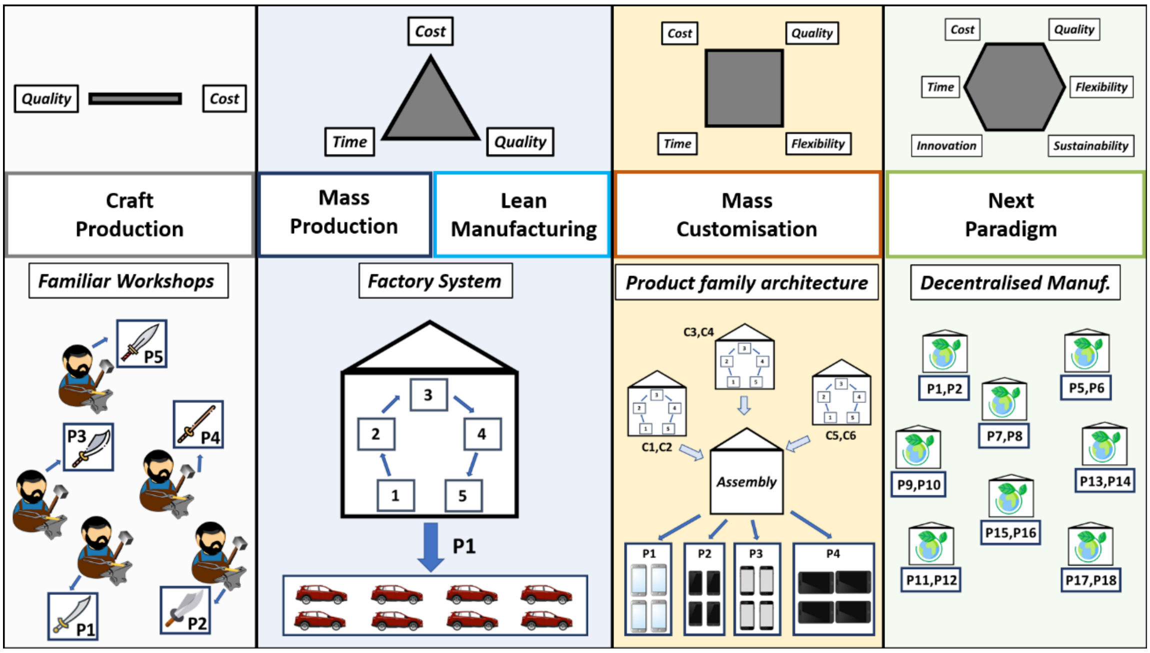


Figure 2.3. Different competitiveness strategies followed by the different manufacturing paradigms (Mourtzis and Doukas, 2012). In CP, each manufacturer delivers high-quality and differentiated products (P). MP and LM decrease cost based on sequential manufacturing lines and economy of scale, but provide standard products. MC reaches flexibility in the production by applying mass production strategy to the interchangeable components (C) that are finally assembled to create a wide range of products. The next paradigm tends to decentralisation to improve flexibility and incorporates sustainability and innovation for adapting to the new market.

The expansion of the centralised manufacturing model led to large-scale processing plants capable to supply national and even international demands. It enabled movement of production far away from the target market –even offshoring– seeking cheaper labour and taxes to keep decreasing costs. As a consequence of such centralisation, the concept of ***supply chain*** arose: the provision of bulk raw materials to the factories, that were then transformed, and left the facility as finished products that were transported to reach the customers.

2.3.3. Lean Manufacturing (1980 – 2000)

The success of MP caused saturation of the market. Product differentiation was then needed for beating competitors, and focusing on quality improvement was considered a good option. However, high-quality products were more costly to produce, implying loss of competitiveness. Lean Production (LP) is acknowledged as an improvement of the MP paradigm that took place in Japan (e.g. Toyota Motor Co.) during the 1980s. LP raised product quality standards without increasing the market price (Apte and Goh, 2004). Process optimisation and innovation, aiming at the elimination of waste (Hodge et al., 2011), were the goals of this scheme. The factory layout was improved, undergoing a restructuring into manufacturing areas, buffers for semi-finished goods and an assembly area. This segmented factory model allowed gains in flexibility and in-process quality, whist minimising inventory and manpower excess (Wiendahl et al., 2007).

This idea of process intensification was then extrapolated to other agents participating in the commercial activity that centralised manufacturing systems created. Business logistics –i.e. later named supply chain management (SCM)– started gaining great importance for lowering total cost and gaining competitiveness. A supply chain is defined as the integrated system synchronising a series of interrelated business processes, from the production of raw materials until the final product reaches the consumer (Fahimnia et al., 2013). From the 1950s, SCM has evolved together with manufacturing processes, and it has become one of the largest areas of academic study, research, and business practice (Ballou, 2006).

2.3.4. Mass Customisation paradigm (2000s – 2010s)

New frontiers in business competition were appearing with the development of economies and the proliferation of companies. The idea of treating the customers as a large homogeneous market was no longer acceptable, and new market opportunities were found implementing demand fragmentation. Through the application of new technology and management methods, companies abandoned the specialised mass production techniques to survive in an increasing competitive market. The new goal was the development of flexible production lines capable to offer a wide range of high-quality and affordable products and services, thus satisfying customers' individual needs (Spring and Dalrymple, 2000). Manufacturing shifted to ***Mass Customisation***.

Mass Customisation paradigm (MC) heightens the variety of supplied products while maintaining near-mass production efficiency (Da Silveira et al., 2001). It relies on centralised practises and considers economies of scope and scale at the early design stage of the product-realization process. Manufacturing comprises product family architecture (see *Fig.2.3*), where production lines are based on modularity and commonality (Tseng and Jiao, 2001). Economy of scale is achieved at the component level, while scope of high variety is achieved in the final assembly by using flexible/reconfigurable manufacturing systems (Hu et al., 2011). Advances in computational science led to the development of automated production lines. New computer integrated manufacturing technologies allowed short product life cycles and increased efficiency, also enabling quick modifications of the production process (Pine, 1993). The automotive, electronics or software industries are examples of industries that have adopted MC manufacturing regime and supply customised products without substantial trade-offs in cost, delivery, and quality (MacCarthy et al., 2003, Qi et al., 2014).

2.4. Future of Manufacturing

During the last 20 years, the complexity of the market has been increasing relentlessly. The presence of volatile demands, fierce competition between numerous companies, and high innovation pressure, have motivated a change in the marketing strategy (Kühnle, 2010). Over the evolution of manufacturing reviewed above, the prevailing financial strategy of firms has aimed at making their business the most attractive possible to current and potential shareholders (Hu, 2013). However, by the first decade of the 2000s, Martin (2010) acknowledged that companies prioritising customer satisfaction were outranking their competitors –e.g. Procter & Gamble leads its sector by following the statement of purpose: "we will provide branded products and services of superior quality and value that improve the lives of the world's consumers" (P&G, 2020). The idea of maximising shareholder value was shifting to a more dedicated focus on clients. This notion starts to deviate from the principles of MC paradigm, that aims to offer a wider range of products for the customers to choose, rather than satisfying individual demands. A change in the settled manufacturing methods is taking shape once again.

The emerging manufacturing paradigm (see *Fig2.2* and *Fig2.3*) has been therefore firstly fuelled by the idea of placing user satisfaction as the priority, and thus gain competitiveness in an increasingly saturated and heterogenous market. To achieve individualised products supply, a modification of the existing production methods is then required. The traditional way of product design, commonly owned by the manufacturer, must change. In MC, professional designers were traditionally in charge of product design. The manufacturer, after identifying existing regional markets, designs a range of products. Conversely, the new strategy modifies the product design concept to involve the customer in design and creation (Hu, 2013). This notion drives manufacturing one step further than MC in terms of personalisation. Providing individualised products is the target of the manufacturing systems and, to make that goal feasible, very flexible production methods must be developed.

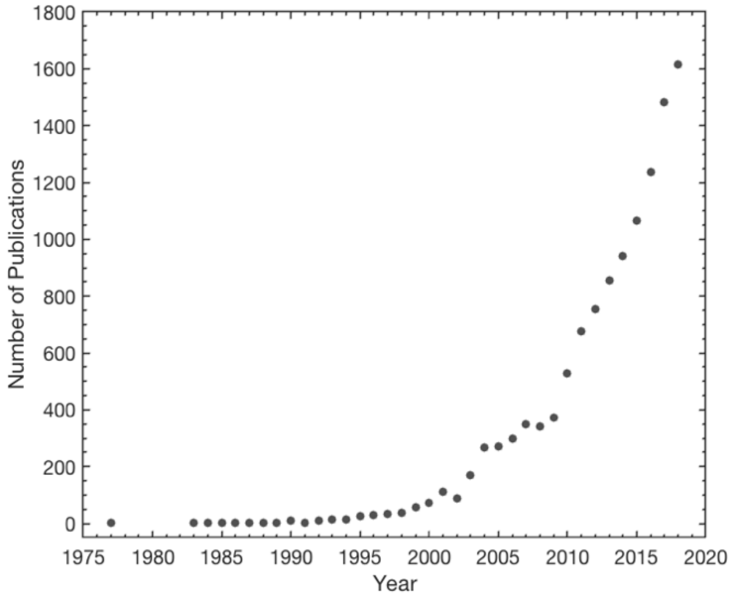


Figure 2.4. Evolution of the number of published documents regarding 'Sustainable Manufacturing' (Scopus database). Research in Sustainable manufacturing started in the 1980s showing an exponential growth in the last decade.

A second driver is the increasing concern about developing sustainable manufacturing systems. During the last decades of the past century, industrial activity did not show any special concern about the damage that it was causing to the ecosystems (Johnston et al., 2007). The environmental disasters that occurred in the world during that period, –e.g. Bhopal or Chernobyl tragedies– motivated governments to impose regulations on environmental health and safety (Haapala, 2013). The concept ‘sustainability’ appeared as the solution to rising worries about contamination and resource depletion, and it was imperatively incorporated to production systems.

Sustainable manufacturing can be defined as “the creation of manufactured products accounting the triple bottom line pillars: economic, environmental and social factors” (Akbar and Irohara, 2018). *Fig.2.4* shows the growth of sustainable manufacturing systems in research. Therefore, the new manufacturing systems comprising the new paradigm must reduce the environmental impact and offer advantageous social and economic scenarios over existing processes.

The increasing preference for ‘green purchasing’ from buyers also influences how firms manufacture goods (Sao and Ünal, 2019). Naturalness, ethics and environmentally friendly production are factors leading to changes in the current manufacturing model.

Finally, empowerment of the customer claiming ‘the product I want and right now’, creates a need for the industry to minimise delivery time. MC was able to shorten the manufacturing time with the integration of computers in production. However, the predominant centralised manufacturing model relies on long and rigid supply chains that imply long delivery times. This suggests that the upcoming long-term paradigm might not be based on centralisation.

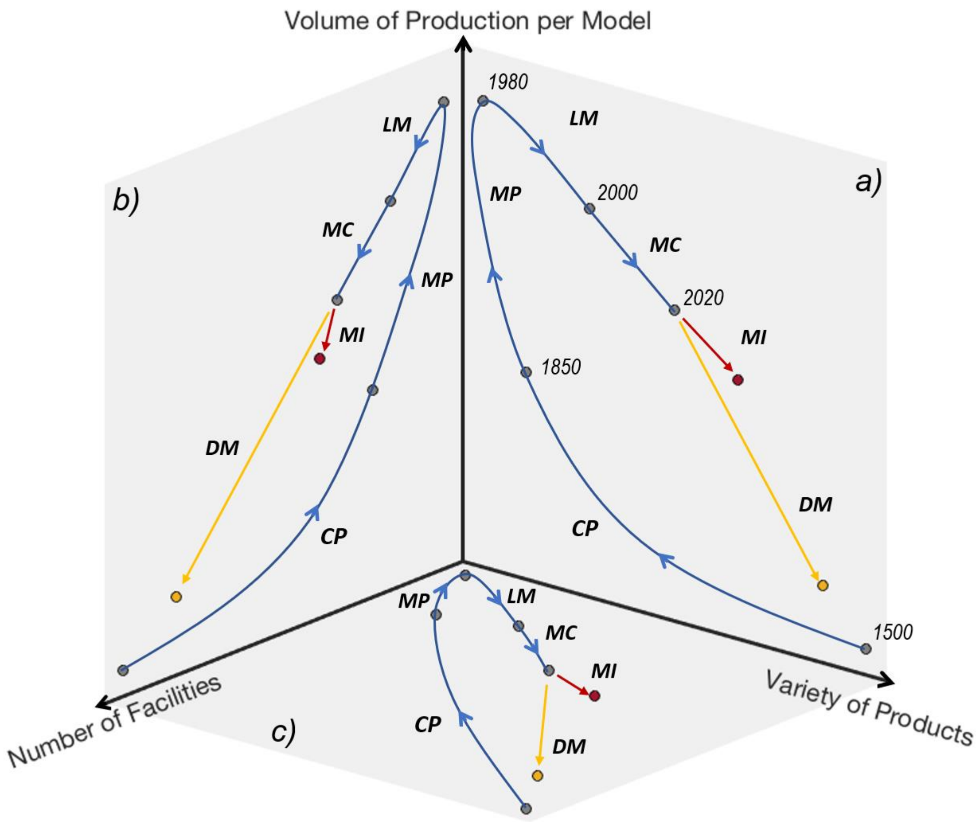


Figure 2.5. Characterization of the different existing manufacturing paradigms through history, namely Craft Production (CP), Mass Production (MP) and Mass Customisation MC). It also includes the two competing paradigms for leading the future of manufacturing: Mass Individualisation (MI) and Distributed Manufacturing (DM). Each side of the 3D graph defines each method in terms of a) Variety of Products vs Volume of Production per Model, b) Number of Facilities vs Volume of Production per Model, and c) Number of Facilities vs Variety of Products. MI follows the trend of the industrialised paradigms based on mass production, while DM closes the cycle approaching the initial CP model.

Figure 2.5 plots the evolution of the existing manufacturing paradigms already described within this chapter. Each production method has been characterised by three main features, namely variety of products (x axis), number of manufacturing facilities that produce the item (y axis) and volume of production per item (z axis). It can be observed how the historical trend has firstly evolved from CP, which comprises a high number of facilities producing differentiated goods in a very low volume per product and facility, to MP that directly opposes the previous paradigm by gathering the production in a few number of high-volume facilities that minimise their product portfolio. LM is still based on MP principles but optimising both manufacturing process and business logistics. However, the need of developing more flexible production lines led to establish MC as the preferred manufacturing method, which involves an increased number of facilities. Despite production is still very large, the production per model is lower due to the high variety of items offered to attract consumers. The trend has been therefore inverted, as Figure 2.5 depicts.

Below, the two prevailing alternative manufacturing paradigms –i.e. Mass Individualisation (MI) and Distributed Manufacturing (DM)– approaches for achieving personalisation and sustainability, are presented. These differentiated models are also depicted in *Fig.2.5*, which shows how MI follows the current trend of multiplying manufacturing facilities while keeping mass production and offering a much more extensive range of products. Conversely, DM represents an abrupt shift in manufacturing and a return to strategies from the past –i.e. similar to CP– that greatly increases the number of facilities and the variety of products that are produced at small-scale. This competition for leading the future of production methods can also be understood as a confrontation between Centralised and Decentralised Manufacturing Systems.

2.4.1. Mass Individualisation

Mass Individualisation (MI) or Personalisation compiles all the efforts that high volume production lines have taken for adapting to the new market demands. This paradigm can be taken as the next step on the natural course of the centralised industrial-based processes.

Innovation technologies have facilitated new strategies for product design and development (Dodgson et al., 2005). The continuous implementation of the information and communication technology (ICT) has brought massive improvements to high-volume industrial manufacturing processes. The manufacturers can improve efficiency and optimise the processing systems, thanks to the increasing simplification of data sharing and data processing. ICT developments also enable database marketing and eases the interaction manufacturer-consumer, so the former knows the latter’s desires, feedback and innovative ideas.

These advances in digitalisation, coupled with cutting-edge engineering –e.g. assembly operations using jigs and fixtures (Kakish et al., 2010)– have led to automated and flexible manufacturing processes. The open-platform architecture products (OAP) arise as the basis of MI paradigm (Koren et al., 2015). OAP comprise an open-hardware platform integrated with multiple qualifying modules that the end-user manipulates using software. The product design has been therefore democratised, and any motivated user can use advances and accessible technologies to develop an individual product (Sikhwal and Childs, 2019). Industry 4.0, focused on developing smart factories based on fully automated production processes (Muhuri et al., 2019), without any human intervention (Wang et al., 2016), is the most current research area in this line of thought.

MI has found application in several markets, with particular success in consumer electronics, furniture or apparel businesses. For example, Levi Strauss sells custom-fitted jeans, or Streif builds housings from client drawings (Zipkin, 2001). However, large-scale industrial processes can only reach customization on few product attributes with acceptable prices and response times in a few sectors (Ferguson et al., 2014). Thus, Levi Strauss cannot yet offer customised colours due to the limitation of large scale customize fabric dyeing (Zipkin, 2001). MI also stakes in high-volume production factories, and consequently underpins the predominant centralised network scheme that generates capital intensive industries. The barriers directly linked to centralised systems –namely high initial investment cost, technological limitations, long transportation distances or high delivery times– will therefore still hold. Those requirements handicap small and medium size companies within a MI scenario, and may prevent this paradigm to become the controlling one in the future of manufacturing (Esmaeilian et al., 2016).

2.4.2. Distributed Manufacturing

Two definitions of Distributed Manufacturing (DM) can be found. DM can be identified as the strategy followed by a single independent company, splitting production in more than one plant to implement differentiation in a product to satisfy several regional markets (Windt, 2014; Kühnle, 2010; Landier et al., 2009).

The second introduces the concept of Distributed Manufacturing Systems (DMS). The value chain is decomposed into different sub-processes assigned to independent agents, that complement each other and collaborate in the production of a good from dispersed locations (Windt, 2014; Rauch, et al., 2015; Lv et al., 2013). DMS arise as an alternative to centralised supply chains in which manufacturing is far from the point of consumption, usually associated with an inefficient use of scarce resources (Srai et al., 2016a).

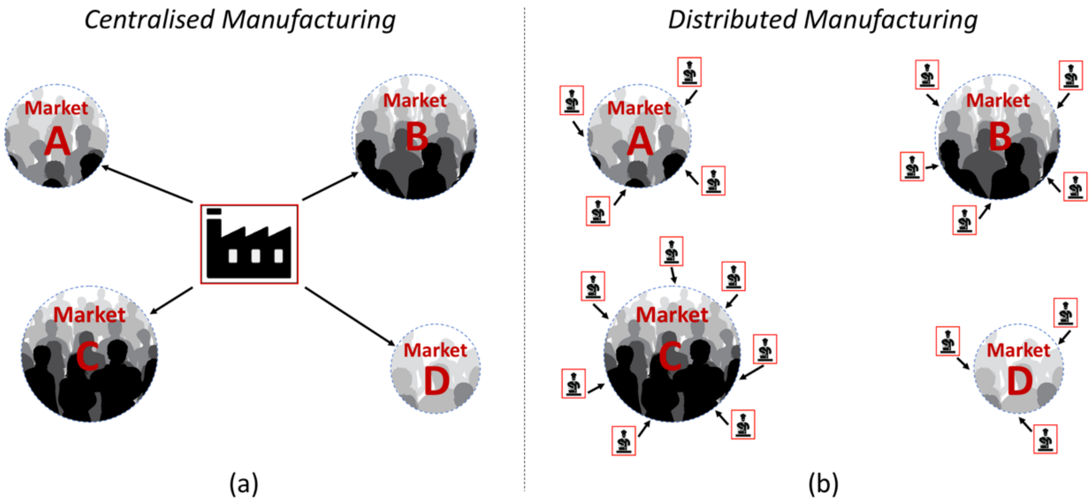


Figure 2.6. (a) Centralised Manufacturing (scenario A) vs. (b) Distributed Manufacturing (scenario B). A net of manufacturing facilities replaces a big plant for supplying the demand of a product in four different markets.

Both definitions share the concept of decentralisation, considering geographically dispersed manufacturing. As previously discussed, this approach directly opposes the historical trend the industry has followed, based on a systematic centralisation of manufacturing (see *Fig.2.5*), and suggest to apply ancient business structures while using the updated technical resources that are available today. In centralised manufacturing systems (CMS), raw materials are transported to large throughput factories, where finished products are fabricated with limited customisation, and then distributed to the customer. In DM, the raw materials sources and methods of fabrication are decentralised, and the final product is manufactured in small quantities close to the final customer (see *Fig.2.6*). Some authors coined the term ‘Re-Distributed Manufacture’ (RDM) to the production system that incorporates small scale and local production to DMS, and thus differentiating from DM (Freeman and McMahon, 2019; López-Avilés et al., 2019; Luthra et al., 2019). However, here it is assumed that RDM is a natural evolution of DM and those two terminologies refer to the same concept.

The main attributes of DM are therefore small (or micro) scale production units, located close to consumers to enable flexibility in production and on-demand supply (Kumar et al., 2019). Local variation or mass customization can be created from small-scale, flexible geographically distributed manufacturing facilities (see Chapter 3). A fast response on production capacity and product design could be achieved, thus enabling just-in-time delivery (Srai et al., 2016a). Furthermore, DMS aim at limiting long distance transportation to just only specific raw materials and data, together with the development of a transport network for the last-mile logistics (Rauch et al., 2016). As a result, the supply chain is shortened, and energy use related to distribution and storage will therefore decrease, as well as the caused emissions (Srai et al., 2016a).

Despite all these benefits of decentralisation, there are some drawbacks to be overcome. As a result of creating a dispersed network of small-scale production facilities, the economy-of-scale cost optimisation is lost. The decentralised structure also requires high capital, and traditionally the complexity of management led to a loss of efficiency in comparison with automated central high-volume production factories (Matt et al., 2015). In addition, quality is a concern of DMS, and many projects have aimed to improve coordination of decentralised systems to provide high-quality products with short delivery time following consumers demand (Lv et al., 2013).

To face all these drawbacks, DM is underpinned by the following:

- New available manufacturing technologies –e.g. Additive manufacturing and modular manufacturing– that allow small-scale production at competitive cost and increasing production efficiency and flexibility (Freeman and McMahon, 2019).
- Digital economy, minimising the cost of logistics and the non-production stages of the manufacturing processes (Kagermann, 2015; Maslarić et al., 2016).
- The exponential growth of ICT and the processes enabled by the Internet of Things (IoT) (Miranda et al., 2019), that have closed distances between manufacturers and consumers (e.g. via app). ICT has promoted integration of manufacturing and service, and enabled outsourcing and crowdsourcing to create better customer service by simplifying processing of information (Jiang and Leng, 2017).
- The new sustainable business models, such as "local to local" or "local to global", that implement Circular Economy on a small-scale manufacturing basis (Freeman and McMahon, 2019; Srai et al., 2016b). Some existing business examples are Interface –sustainable carpets manufacture–, Gazelle –electronics refurbishing–, or Vitsœ –chair reupholstering– (Boken et al., 2016).

2.5. Food Manufacturing

Eating food is essential for any human being. Besides being one of the basic needs for life, eating food is also a social process. It is part of the traditions, rituals, beliefs and daily life of people (Toussaint-Samat, 2009). Existing gastronomies, comprising dissimilar farming methods, age-old skills and culinary techniques, show cultural diversity and a tourism resource that boosts the economy (Martins, 2016; UNESCO, 2010).

2.5.1. Evolution of Food processing

Food processing is the alteration of foods from the state in which they are harvested or raised to better preserve them and feed consumers (Floros et al., 2010). Just as manufacturing, the way food has been processed has evolved over time *(see Fig.2.7)*. The timeline for the evolution of this specific sector, however, is slightly different to the evolution of conventional 'mechanical' industry. The important differences between food manufacturing processes and mechanical product industries –i.e. product decay, maturing cycles, cleaning, specific packaging or delicate handling among others (McIntosh et al., 2010)– together with the fact that food can be preserved and processed at home, have delayed the implementation of the manufacturing paradigms previously described.

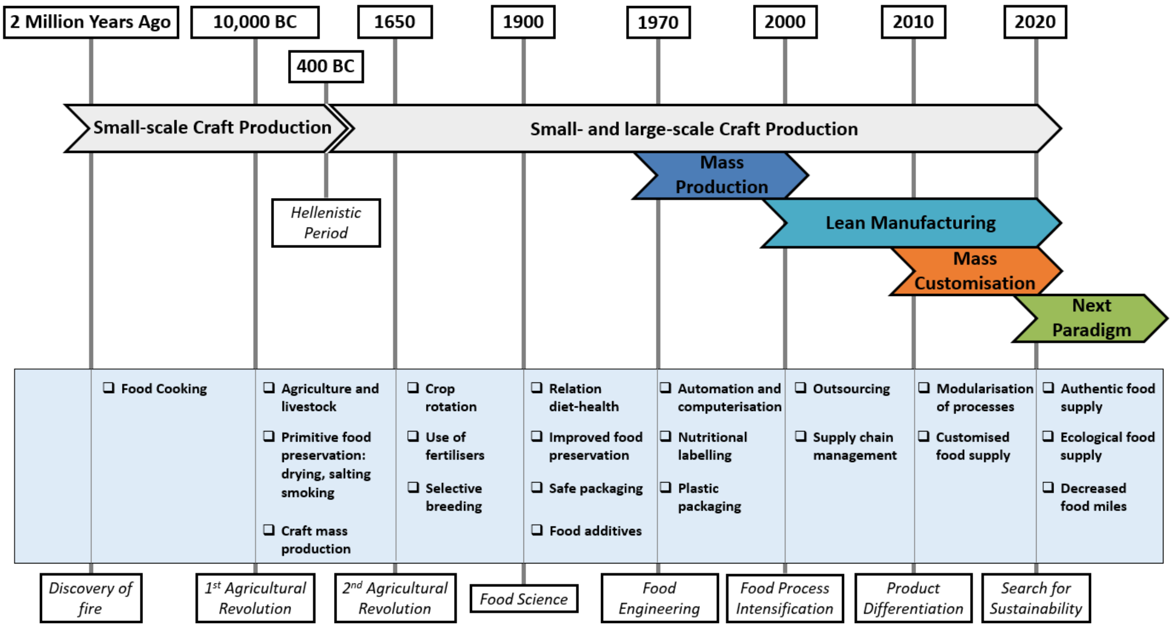


Figure 2.7. Evolution of food processing. The manufacturing paradigms have been applied to food processing at different dates than conventional 'mechanical' industries. The approximated relevant dates and main drivers are shown, together with the most important achievements in food processing during each period.

The world has progressed through hunter-gatherer, agricultural and industrial stages. The first signs of food processing date back 2 million years ago, when fire was discovered and used for cooking (Wrangham, 2009). Later, still in prehistoric times, humans learned how to transform, preserve and store food in a safe way (Floros et al., 2010). The First Agricultural revolution (ca. 10,000 BC) involved the transition for many human cultures from a lifestyle of hunting-gathering to one of agriculture and settlement (Bocquet-Appel, 2011). Sophisticated methods for food preservation, e.g. fermentation, drying or preservation with salt, were also developed to prevent food loses caused by spoilage and survive during times of scarcity. Food processing was therefore one of the first successful technologies and led to the segregation of societies into discrete artisan industries (Weaver et al., 2014). During the following millennium, agriculture and livestock farming spread widely. Local production and mass production using craft methods coexisted, a situation that remains nowadays. Large-scale food production was acknowledged in the Hellenistic and Roman Periods (between ca. 400 BC – 500 AD) for certain kind of foods, i.e. fish-salting, oil and wine production or bread making. Scale of production was achieved using limited machines such as presses, mills or dough mixers (Wilson, 2009). In modern times, the Second Agricultural Revolution (XVII-XIX centuries) supposed a great enhancement of food production by the implementation of innovative ideas such as crop rotation, selective breeding, or the use of fertilisers (Mingay, 1977). The improved food availability resulted in population growth, which led to the Industrial Revolution and changed the whole manufacturing paradigm.

All the existing preservation methods by that time were implemented without a certain understanding of the underlying science. The greatest milestones in food processing were achieved during the XX century, when food science and food engineering arose (see Section

2.5.2). The direct relationship between diet and heath became irrefutable, and major achievements –drum drying, aseptic packaging, rapid freezing technology, controlled atmosphere processing or UHT process among others– were accomplished (Welch and Mitchell, 2000). Large-scale mechanised food processing was therefore enabled during this period (Weaver et al., 2014) and, with the automation and computerisation of food processing lines by the 1970s (Welch and Mitchell, 2000), the MP paradigm was then applied to food manufacturing. As a result, food industry emerged, and the global food sector evolved (see Section 2.5.3). By the first decade of XXI century, the application of LM concepts –i.e. to improve mass production efficiency focusing on outsourcing, cooperation, networking and agility– to food industry are studied (Lehtinen and Torkko, 2005; Cox and Chicksand, 2005; Engelund et al., 2009).

Currently, MC paradigm is still maturing for food industry (McIntosh et al., 2010; Calegari et al., 2020). The ability of large-scale food processes to customise products without penalty is limited. Previous studies have identified the barriers for MC to be successfully applied to food processing, which include inflexibility to enhance the modularisation of the processes (McIntosh et al., 2010), restrictions in postponement opportunities linked to the food perishability (Kouki et al., 2013), limitation in handling mass-customised food (Matthews et al., 2011), difficulties on displaying nutritional information for customised products (Balcombe et al., 2016) or customer's acceptance of customised foods aggregated value (Ngpal et al., 2015). A better suitable manufacturing method should be therefore found for this sector to adapt to the new scenario, where meeting customer satisfaction is the main objective for the current business strategies.

2.5.2. Food Process Engineering

With the exponential growth of the population and the segmentation of work by the end of the XIX century, the necessity of food supplying became crucial. To improve the scope and quality of food supply regardless geographic distances or seasonal timeframes, ***'food engineering'*** emerged as a whole field of study (see *Fig.2.8*).

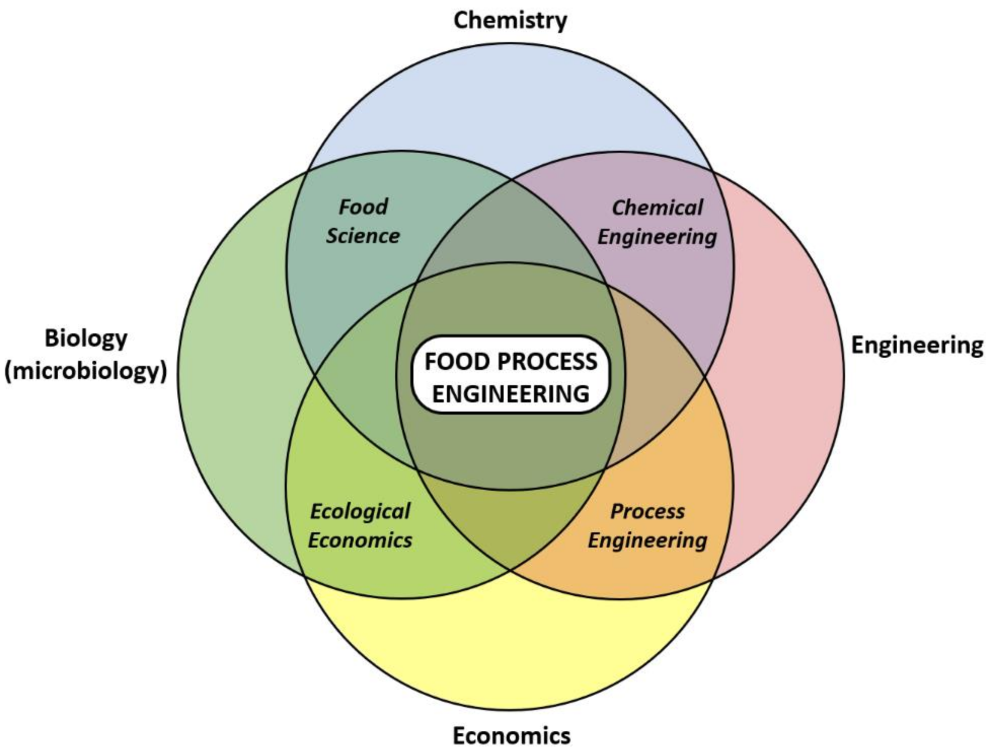


Figure 2.8. Venn diagram showing the interdisciplinary nature of food process engineering.

Food engineering (or *food process engineering*) is based on the application of food science principles to the established techniques of chemical process (Maroulis and Saravacos, 2008). Historically, it evolved from early preservation techniques –i.e. drying, salting, fermentation and cooling– to later development of thermal treatments (e.g.

pasteurisation and mechanical refrigeration), applying the knowledge acquired from bacteriology and microbiology. During the past five decades, food engineering also has incorporated further scientific principles (e.g. transport phenomena and heat and mass transfer) to perform process design (Heldman and Lund, 2001). With the integration of computational tools, mathematical modelling of food processes was coupled with computer simulation of operations, enabling the optimisation of product variables, such as nutritional value (Liu et al., 2019), quality characteristics (Rodman and Gerogiorgis, 2016) or flavour (Taylor, 2009). Therefore, food engineering currently aims at the optimisation of the food processes from the earlier design stage, also enhancing the efficiency from an economic and sustainable point of view (Egilmez et al., 2014).

2.5.3. Importance of Food Production Systems: Food Industry and Food Supply Chain

Simultaneously to the development of food engineering, a sector of industry dedicated to food emerged and progressed. The ***food industry*** aims to provide plentiful, varied, inexpensive healthy and safe foodstuffs, and simultaneously take advantage of all the commercial benefits that the food market generates (Nestle, 2013). Nowadays, the food industry is a major sector in the world economy. It relies on sophisticated food production and traceability, innovations in food formulation, processing, packaging, storage and distribution, which ensure quality and safety and thus the delivery of nutrients for human health (Roos et al., 2016).

The global food system has had an important role in improving human welfare worldwide. A reduction in the proportion of undernutrition in developing regions, from 23.2% in 1990–92 to 14.9% in 2010–12, has been achieved (Keating et al., 2014). There is still, however, one in nine people in the world suffering from chronic hunger (Kamonpatana, 2019). Furthermore, the forecasted growth in global population by the year 2030, together with the expected impacts of climate change, demands an increase on food production by 50% (Tassou et al., 2014). This scenario makes essential to keep implementing the current food systems, increasing productivity while reducing the high environmental impact associated to the activity of food sector.

The food sector represents a large percentage of total manufacturing value added in most countries (Miranda et al., 2019). Taking the United Kingdom as an example, the whole agri-food sector is the largest industry sector in the UK, with a contribution of £121 billion (6.7% of the national GVA) to the economy (DEFRA, 2019a) and comprising 3.6 million employees (12% of the national employment) in 2018. The growth of the food sector is demonstrated in an economic regression scenario, showing an 1.5% increase in the productivity of the food chain, while the wider economy decreased by 0.2% in 2017 (DEFRA, 2019b). Moreover, the expenditure in food represents an important share of the family budget, reaching an averaged 10.6% over all households (DEFRA, 2019a).

The food supply chain comprises several stages, shown in *Fig.2.9*: (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 and (vi) sale. Each stage involves financial cost, energy consumption and environmental impact (Tassou et al., 2014). 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, having a similar ratio (12%) to the manufacturing share (13%) (DEFRA 2013; AEA, 2007).

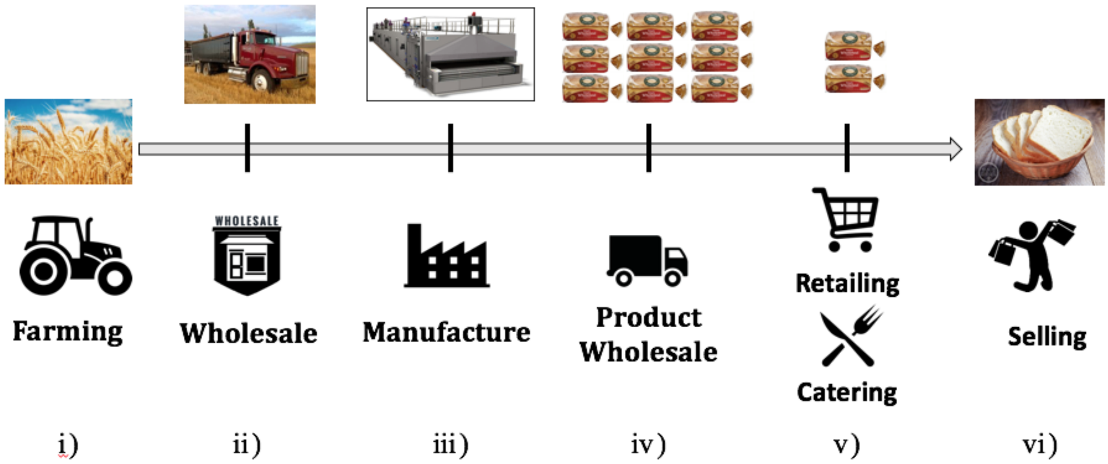


Figure 2.9. Different stages comprising the food supply chain. Sandwich bread is used as an example.

2.5.4. Centralised vs Decentralised Manufacturing in Food Industry

It has been shown how food manufacturing has followed a similar trend that manufacturing systems but at delayed times. Conventional food manufacture has tended to develop large food plants with long distances for retail (Brodt et al., 2013; Angeles-Martinez et al., 2018). Although this approach is efficient in a manufacturing sense, exploiting economies of scale, the centralised manufacturing system also implied inflexibility on the production, and significant costs and environmental impacts linked to transportation (Mourtzis and Doukas, 2012). The standardisation of the food products in CMS, with the consequent loss of the traditional characteristics that identify different regional foods, represents a loss in competitiveness within the current diversified marketplace (Tseng and Hu, 2014). The food industry has shifted from a supply-based approach to a demand-based approach. Mass customization, delivering differentiated or personalized products with near mass production efficiency, is the goal for many companies (Demartini et al., 2018). But mass customization with centralization still creates lengthy and rigid supply chains (Cholette and Venkat, 2009).

Distributed Manufacturing (DM) has been recognised as a feasible solution to satisfy a market with an increasing individualised demand, offering customer-specific product variants in a short delivery time, authenticity, and involving sustainable and ethical manufacturing processes (Rauch et al., 2017). A restructuring of food manufacture into decentralised small-scale networks could increase the impact of local food –i.e. comprising distinctive regional characteristics and using ecological raw materials and methods– and customised food production (Cottee, 2014).

DM ambitions are a revolution on how products are made and how they are distributed (Wang, 2018). Short Food Supply Chains (SFSC) and Alternative Food Networks (AFN) comprise alternative scenarios that shorten the supply chain and develop a local food economy (Chiffoleau et al., 2019). SFSC involve a horizontal relationship between producers and consumers by reducing distances and intermediary actors (Sellitto et al., 2018). AFN add up synergies between agriculture, manufacturing and consumers, going one step further in terms of shortening the supply chains. They oppose technology treadmill, promoting a restructuring from agro-industrial forms of production to smaller scale family farms that supply nearby urban areas (Jarosz, 2008). Farmer markets can supplement food supply, providing wholesome food products with an ethical basis treadmill agriculture lacks (Blay-Palmer and Donald, 2006).

SFSC and AFN minimise food miles, so the products can be sold fresher and with less preservatives. Shorter transportation also would reduce damage and spoilage, preventing nutrient loss (Galli and Brunori, 2013). These scenarios 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 these methods can contribute to food security (Cerrada-Serra et al., 2018; Moragues-Faus and Carroll, 2018).

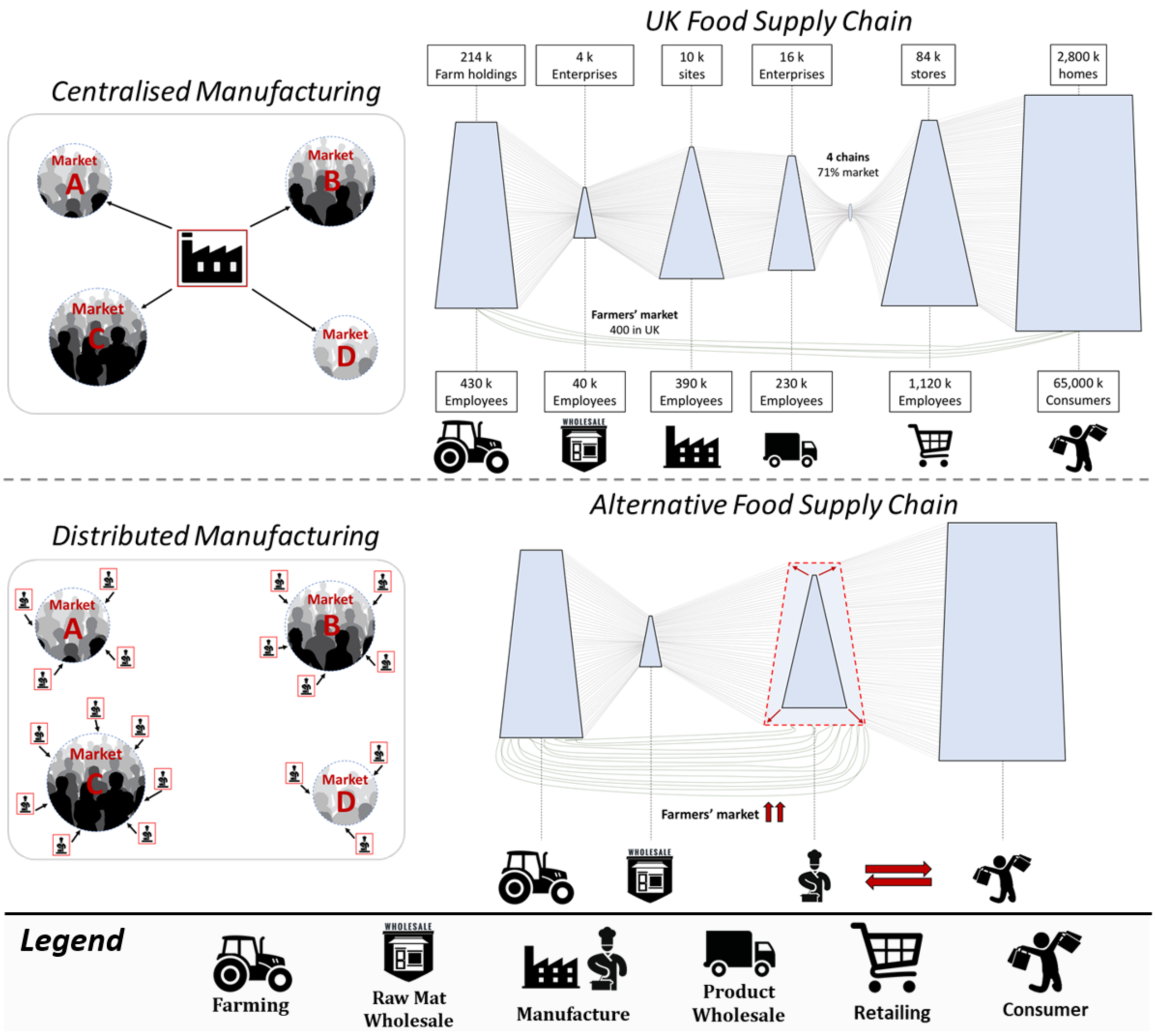


Figure 2.10. Food product supply chain. (a) Centralised Manufacturing vs. (b) Distributed Manufacturing. Using UK food supply chain (DEFRA, 2017) as an example (upper figure), an alternative supply chain based on decentralisation would require a horizontal relationship between manufacturers and customers (lower figure). A rise on the number of manufacturing facilities is required and a direct supply of some raw materials (those available for this purpose) from the producers would shorten the length of the supply chain.

Fig.2.10 compares the current UK centralised food supply chain and an alternative food system based on Distributed Manufacturing. In the UK, manufacturing is in a short number of sites (compared to the number of farm holdings, supermarkets or homes) that gather an average of 40 employees per site. Food provision shows a significantly distorted scenario, where the four leading supermarket chains –Tesco, Sainsbury's, Asda and Morrisons– have 71% of the market (Bonanno and Busch, 2015), demanding significant volumes per product and hampering market access (Vasquez-Nicholson and Phillips, 2018). The alternative sustainable supply chain, based on decentralisation, would require expansion of manufacturing facilities, located close to the consumers and minimising intermediates. Seasonal products would be directly provided by farm markets with an increased supply share, and only raw materials with limited availability would travel miles. Scenario B results in shortening distances on the supply chain, elimination of barriers for food distribution, scale reduction, commitment to local actors, organic production and sustainability.

Although the balance between increased production costs and decreased transport cost in decentralized scenarios needs further study, DM could be used for the emerging SFSC model 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).

2.5.5. Distributed Manufacturing paradigms in Food Industry

There are currently three manufacturing paradigms of potential practical application of DM principles in the food sector: Additive Manufacturing, Modular Manufacturing and Artisan Manufacturing.

2.5.5.1. Approaches to DM: Additive Manfuacturing

As an attempt for making the DM systems feasible, Additive Manufacturing (AM) has become major research area during the last decade (Wittbrodt et al., 2013; Ngo et al., 2018; Mitchell et al., 2018; Challagulla et al., 2020). This cutting-edge technology encompasses all those technologies that enable “3D printing” of physical objects. AM blends aspects of MP, CP and MI, supplying cheap and convenient goods, with a very fast delivery, and providing freedom to the user in terms of product design (Lipson and Kurman, 2013). Solid objects are directly created from CAD (computer-aided design) models, developed by a single device with no retooling, and thus comprising digital precision and high reproducibility (Hu, 2013).

AM was originally invented to fabricate metal, ceramics or polymer-based objects, but has found application in the food sector. The goal is to print food materials with complex geometries, customised textures and with tailored nutritional values (Sun et al., 2015; Severini and Derossi, 2016). Techniques used for food 3D printing are extrusion-based processes and inkjet printing –liquid material supply–, selective laser sintering and powder binding deposition –solid material supply–, and bioprinting –cell culture deposition (Femmer et al., 2015; Godoi et al., 2016).

AM could simplify conventional food supply chains. The approach to on-demand economy (Gurvich et al., 2019; Lipton et al., 2015) would return manufacturing to a local basis, reduce transport volume and packaging, and minimise distribution and overhead costs (Liu et al., 2017; Jia et al., 2016). AM would also decrease the capital needed for start-ups (Hannibal and Knight, 2018), thus lowering the capital barrier linked to centralised manufacturing systems. However, technological limitations will still exist. Not every food product can currently be 3D printed, and research is yet focused on a limited food variety such as cheese, dough, sugar, chocolate, gelatine or meat. There is also still a need to enhance printing accuracy and productivity, and improved flavour and texture of products must be achieved for this technology to become feasible in wide commercial use (Liu et al., 2017). Finally, consumers' awareness and acceptance of these type of foods might be a challenge in the increasing ecological and authentic food demand (Dick et al., 2019).

2.5.5.2. Approaches to DM: Modular Manufacturing

Modular Manufacturing (MM) was originated in the chemical engineering sector as a solution to find flexibility in production, and thus adapt to shorter product lifecycles and volatile market demands (Radatz et al., 2017). MM follows the principle of process intensification (Reay et al., 2013; Kim et al., 2017). On this basis, MM develops small-scale and flexible production lines, comprising scalable preassembled blocks/modules that integrate multiple unit operations in the least possible number of physical devices (Baldea et al., 2017).

Applications of MM to the food sector can be cited. Complete ice cream process lines with different sizes (IceTech, 2019) and modular craft breweries (Schulz, 2019) are examples currently available. This manufacturing model might forego the capital intensity given by the economy of scale, and increase the environmental impact associated to modules transportation (Sánchez and Martín, 2018). However, small modular plants are quick to construct and can be located either close to customers or remote raw material sources, thus minimising logistic costs. MM also comprises low investment risks to exploit resources, which, together with a potential reduction in capital and/or energy intensity, makes it feasible (Bielenberg and Palou-Rivera, 2019; Garcia and Trinh, 2019).

2.5.5.3. Approaches to DM: Artisan Production

The continuous industrialisation of the food processing methods has increased consumer scepticism about food quality and safety. Many studies endorse the preference of the consumer for traditional, domestic and regional food, over industrial and imports (Pieniak et al., 2009; Toler et al., 2009; Fernqvist and Ekelund, 2014). Consumption of local food positively affects quality and naturalness perception (Migliore et al., 2015), in contrast with industrialised food characterised by standard production processes and long food miles travelled (Giampietri et al., 2018).

Artisan Production (AP) at small scale can provide fresh, trusted and authentic local food, for example following traditional recipes developed by local chefs (Kuznesof et al., 1997). Each craftsman can introduce variations on the product, resulting in local customization and providing flexibility to the manufacturing process. At the very smallest scale, the AP activity can be carried out in domestic kitchens. The so-called '*cottage food manufacturing*', can be integrated in SFSC, showing an increasing share in developing countries (Tutu and Anfu, 2019).

To be considered feasible, AP should step away from the specialist food production, (Maye and Ilbery, 2006). The coordination of the large number of agents needed to duplicate the throughput of a high-volume plant, and the difficulties of the connection between producers and customers, has prevented this model from existing. However, advances on ICT have broken down those barriers, and could give an opportunity to AP to increase market share and not being specifically dedicated to just supply niche markets. AP must face some other challenges. Craft products are typically constructed around the notion of quality, but improved food safety management systems are needed to ensure food control and safety and protecting consumers (Tutu and Anfu, 2019). This paradigm must also refrain from creating luxury food products that customers would buy occasionally (Groves, 2001). Although artisanal food production likely results in higher prices, finding trade-offs among price, business sustainability, effort in manufacture and product quality, must be accomplished (Cope, 2014).

2.6. Solving the scale down problem in manufacturing processes

The broad assessment of the trends of manufacturing systems identifies a tendency to decentralisation. Distributed production causes the scaling down of the manufacturing processes, and therefore foregoing the advantages of economy of scale. However, these small-scale scenarios defined by DM are incompatible to large plant production. The approaches for a small-scale manufacture of pharmaceuticals, using process intensified modular equipment in low-volume production lines, is a noticeable example (Buchholz, 2010). Here, the performance of economy of scale is assessed.

The operating cost of an industrial plant can be divided into fixed and variable costs (Gill et al., 2017; Newnan et al., 2004). *Fig.2.11* represents how total cost typically varies with production at plant scale. Fixed costs (or indirect costs) tend to remain constant and independent of the production rate. At zero-production operation –intercept point– fixed costs still exist, are directly linked to the size of the constructed plant. Conversely, variable costs (direct costs) tend to be proportional to the throughput value until the maximum capacity is reached –e.g. raw materials purchase doubles up for producing the double number of units– and are negligible at zero-production. The sum of fixed and variable costs comprises the total operating cost, defined as the total expenditure for the development of the manufacturing activity in a specific time basis –an accounting cycle of one year is generally assumed. A linear trend can be identified in the variation of the operating cost with production.

Fig.2.12 shows the behaviour of the operating cost per unit of manufactured product, allowing a better understanding of the effect that production scale has on the plant expenses. The initial trend from *Fig.2.11* is inverted and the relation is non-linear. Fixed costs per unit become too expensive at low throughput and drive the unitary cost above the market price, leading to non-profitable scenarios. There is therefore a minimum capacity for the designed plant to be profitable, called breakeven point. Below it, the benefits of economies of scale no longer hold (Ruffo et al., 2006).

This brief analysis of plant economics (a more detailed analysis can be found in later chapters) shows the limitation that fixed costs represent in the profitability of plant operations. Fixed costs are however scalable, i.e. a smaller plant will require less fixed cost that a bigger one. For capital cost estimation at various production scales, power laws are commonly used:

$$C = C_0 \left(\frac{A}{A_0}\right)^n \qquad \text{Eq. 2.1}$$

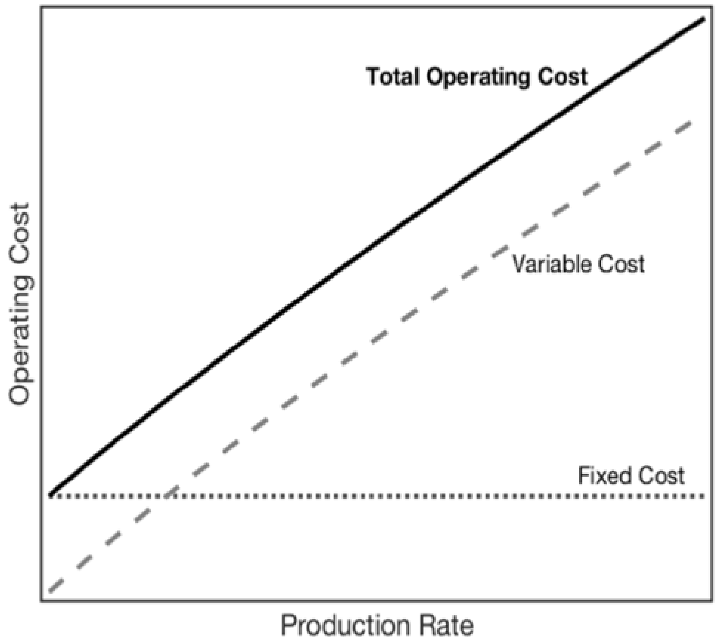


Figure 2.11. Total operating cost in a manufacturing plant, from non-production to maximum plant capacity. A linear trend between this variable and production rate is found, due to the variable cost impact.

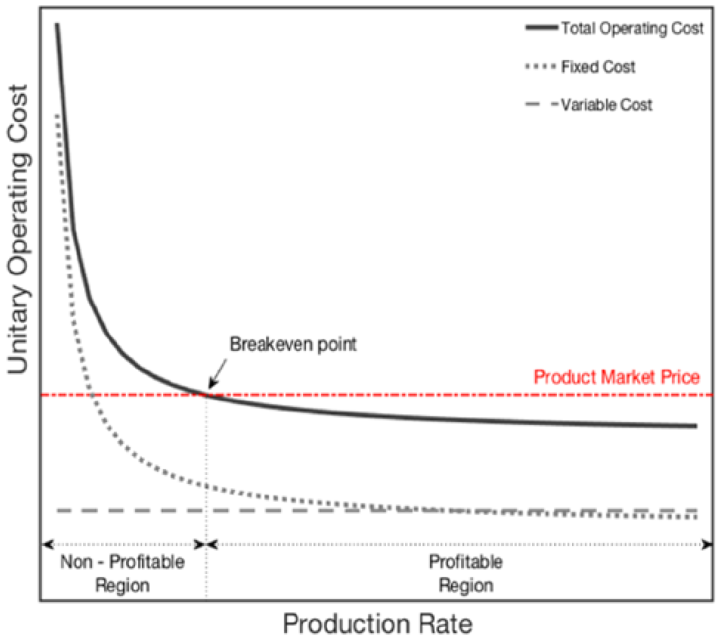


Figure 2.12. Operating cost per unit of product behaviour in manufacturing. The breakeven point divides the operation in profitable and non-profitable regions. An increasing share of fixed cost at low throughput makes the operating cost to surpass the breakeven point.

Where C are the costs of equipment of different capacities, A is a specific variable linked to the size of the equipment, and n is the cost exponent. The generalised s*ix-tenths factor* rule is a widely used example for plant cost estimation, where A is the capacity of the equipment and n is 0.6. In general, the cost-capacity concept should not be used beyond a tenfold range of capacity (Peters and Timmerhaus, 2003), and it applies within minimum and maximum industrial equipment sizes (Maroulis and Saravacos, 2008). Another example is the *two thirds power* rule, where the capital cost is assumed to be proportional to the equipment's capacity with a power relationship of index 2/3 (Reay et al., 2013). In *Fig.2.13*, it is shown how equipment with a ten times higher capacity is not ten times more expensive, but multiplies the cost by just four.

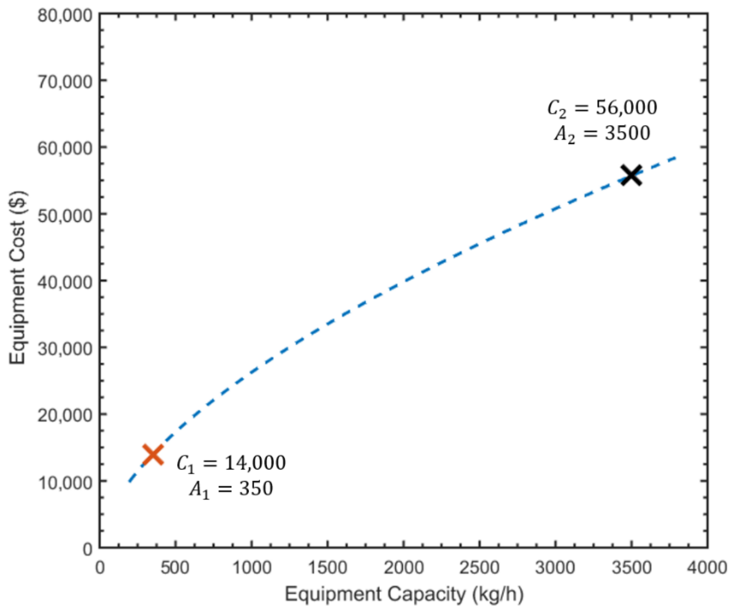


Figure 2.13. Application of the six tenth rule to an equipment that initially cost 14,000 $ for producing 350 kg/h. The same type of equipment with a ten times higher capacity does not cost ten times more (Sinnott and Towler, 2013).

These rules encourage capital investment in large quantities. A technology which allows production capacity to be adjusted economically in small scale may prove attractive. Such alternative, proposed in this work and aimed at food industry, could be Artisan Manufacture due to its inherent low investment capabilities.

At the smallest manufacturing scale per facility, a very large number of "production units" (labour and stores) is required to duplicate the output of a plant. The 'gig-economy' concept, 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; Ritter and Schanz, 2019). 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 digital platforms (Hamari et al., 2016; Sutherland and Jarrahi, 2018), has overcome the limitation of capital investment at low production rates. Advances in ICT have allowed contact between indefinite number of customers and workers (De Stefano, 2016). These ideas set the basis for different manufacturing models on food processing, by analogy with other industry sectors, e.g. Uber and Airbnb.

The restructuring of the production in small (and micro) manufacturing sites, enabled by artisan manufacture, can also allow local sourcing, rapid changes in supply, efficient distribution, direct marketing, smaller inventories, reduced working capital, and improved customer relations and services. Better opportunities to small and medium size enterprises are provided (Rauch et al. 2015). This model may be successful as a result of the common prioritisation of customer satisfaction from artisans, the strong competition among them for attracting clients, and the consumer's preference of local over industrialised food products. The brewery sector in the UK can be taken as a good example of the success of artisan/craft manufacture, with a growth of 184% in the number of microbreweries between 2002 and 2013 (Ellis and Bosworth, 2015).

2.7. Modelling and design of manufacturing processes

In this literature review, many research studies focussed on theoretical approaches of alternative supply chains and distribution systems have been cited. However, there is a lack of study and applied work in local food processing systems (Roos et al., 2016). The perception that locally produced food is far more expensive represents a barrier to companies to opt for this (Donaher and Lynes, 2017; Noseworthy et al., 2011). To fill this gap, this work uses a Process Systems Engineering methodology, to develop a mathematical model for the process simulation of food manufacturing at variable scales.

2.7.1. Process System Engineering

Process System Engineering (PSE) is a relatively new interdisciplinary field – originated during the 1960s– that came under the banner of chemical engineering (Grossmann and Westerberg, 2000). PSE integrates computer science for solving traditional complex engineering problems, and thus devises new process systems or modifies existing ones. As a result, process design methods have experimented major changes during the last three decades. The initial ad-hoc analysis of flowsheets and trial-and-error approaches has shifted to the use of systematic numerical solution techniques, that are currently implemented for both concept and detailed design. Modern optimisation strategies can find those values that maximise the efficiency of the designed systems. Common mathematical packages, such as MATLAB® or Mathematica®, have been incorporated as basic tools in engineering, and process simulators (CHEMCAD®, Aspen®, gPROMS®) or specialised software (e.g. COMSOL® and GeoDict®) have been implemented and commercialised for solving specific models.

In the current oversaturated market, companies must design and operate their manufacturing processes with the highest efficiency and effectivity to win competitiveness. PSE has provided the methods, tools and people to allow industry to meet its needs (Grossmann and Westerberg, 2000). Mariano (2015) points out the high impact that PSE has had in several chemical and fuel companies. For example, Kuwait oil has recently reported 60% capital cost reduction in process design using Aspen HYSYS® (Kapavarapu, 2011) and Dow Chemical claimed to have saved $65 million thanks to Aspen Shell & Tube Exchanger tools (Kolesar, 2010). BASF has optimised the product formulation of the expandable polystyrene production line achieving 30% batch time savings. The modelling and scheduling optimisation of the crude-oil feedstocks has also enabled $2.85 million/year savings in an oil-refinery operating cost (Kelly and Mann, 2003). As the latest instances, process simulator gPROMS has allowed Shell Chemicals to save $0.5 million/year from a redesign of an azeotropic distillation unit; BP reported a capital reduction of $1.5 million in the design of a depressurisation vessel for African offshore oilfield using this software (Process Systems Enterprise, 2019); and Repsol saves around $5 million/year using gPROMS for simultaneous optimisation of the reactor and separation sections in their new propylene oxide process (Martín-Rodriguez et al., 2010).

2.7.2. Mathematical modelling and optimisation of manufacturing processes

A mathematical model is the representation of a system using mathematical language and concepts, to describe, assess and predict the performance, dynamics and evolution of the actual system. The modelling and simulation of chemical processes –also known as process flowsheeting– has enabled a better analysis and understanding of the chemical processes (Foo and Elyas, 2017). Manufacturing systems models are also used to reduce production and design costs, estimate capital investment or evaluate different available technologies and procedures (Martin, 2015).

Within the process flowsheeting, some basic stages should be sequentially accomplished, as shown in *Fig.2.14*:

A. *Product Formulation*. The first step is to select the combination of components comprising the final product delivered to the market. The chosen ingredients will directly affect the process design, i.e. different aggregation states of raw materials require alternative processing. Physical, chemical and biological properties strongly depend on product formulation (Schwartz, 1981). The formula must meet economic and quality constraints, account process feasibility, and provide a product that results attractive to the customers (Lefebvre, 1983). In the formulation of foods, nutritional value, flavour, safety and perishability are additional variables considered.

B. *Production Capacity*. A market analysis should be carried out to estimate the current and future demand of the manufactured product. Also, cost-and-profit analysis is conducted to identify the breakeven point, and, depending on the capital availability, the process throughput is proposed (Peters and Timmerhaus, 2003). Here, the production rate will be a variable that will show the different performance of several manufacturing scenarios in a wide range of throughput values.

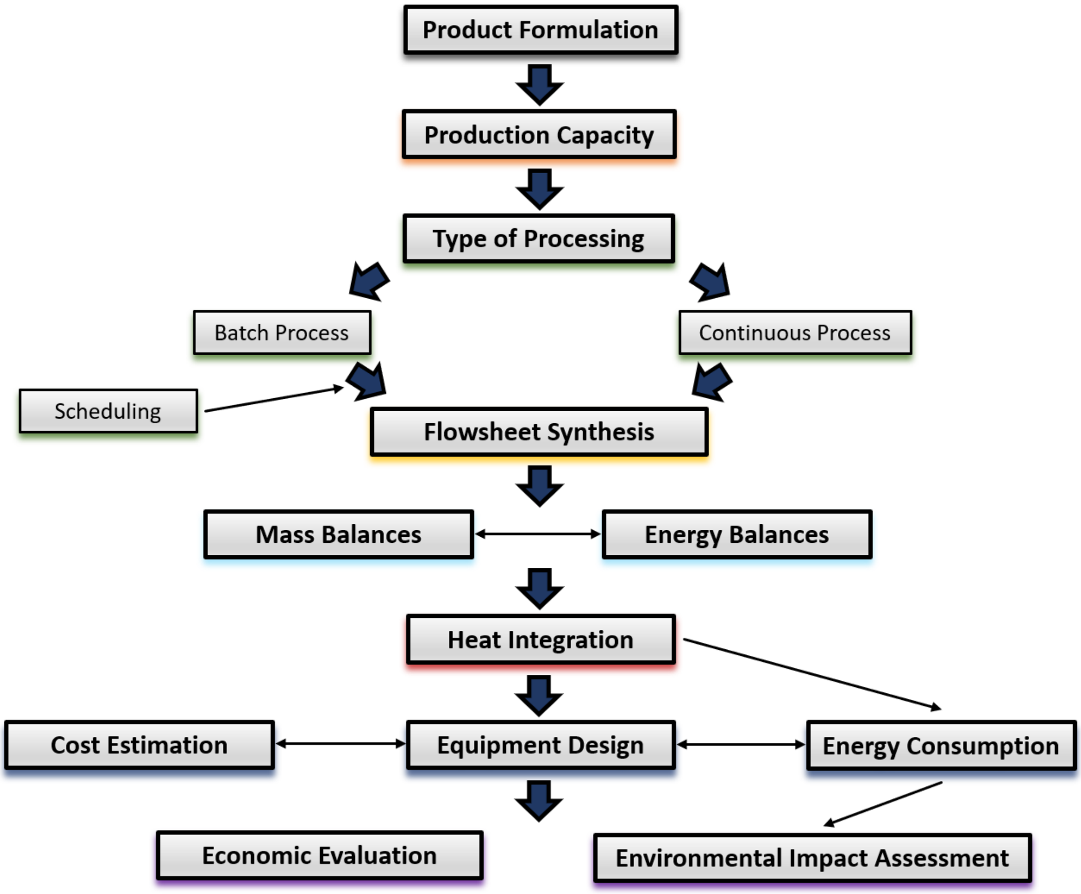


Figure 2.14. Basic stages in the modelling of manufacturing processes.

C. *Type of Processing*. Batch and continuous processing are the two alternative operation methods in manufacturing. To sway towards one of the two options, or integrate both practices within the same process, is the first decision in process synthesis (Douglas, 1988). Batch processes are commonly assigned to small-volume production rates. They usually require less investment costs and are more flexible to product changeovers, but involve scheduling for an optimal performance (Pinedo, 2016). On the other hand, continuous processes are often the most economical-efficient option for large production scale. Operating in continuous enables automatization, decreases labour and improves the control and reproducibility of the process.

D. *Flowsheet Synthesis*. The unit operations comprising the production process are identified. The individual steps that involve physical or chemical transformations – e.g. milling, homogenisation, drying, etc– are based on both scientific principles and gained experience (McCabe et al., 1993). A model for the different units is built. For this purpose, first principles (e.g. mass and energy balances, thermodynamics), dimensional analysis (e.g. dimensionless correlations), heuristic methods (e.g. rules of thumb), experimental data (e.g. kinetic models, factorial design of experiments, empirical correlations) and mechanistic models are commonly used (Martin and Grossmann, 2012). The resulting individual models are finally assembled to formulate a structure for the systematic design of the chemical process.

E. *Heat Integration.* A study for energy recovery in a process can represent large savings in energy cost (utilities) and environmental impact (Sieniutycz and Jeżowski, 2013). High pressure or temperature streams, together with the combustible wastes generated during the process, have energy content that could be potentially recovered. Thus, hot process streams can be used to heat up cold process streams, high pressure gases can feed turbines for power generation, and combustible wastes can be disposed of by burning while producing heat. The trade-offs between capital increase (additional equipment purchase and operating cost) and energy cost savings must be assessed to ensure heat integration worthiness (Sinnott, 2005). Pinch technology used for the design of heat exchanger networks is one example of heat integration methods (Linnhoff, 1993).

F. *Equipment Design.* This step involves the selection, specification and design of the equipment to perform the unit operations previously characterised. The chemical engineering part is limited to the selection and sizing of the equipment (Sinnott, 2005).

If standard equipment can be adapted to carry out the process unit, it generally results in cost reduction. As an example, here, drum dryers of different sizes from a commercial catalogue are adapted and compared to choose the most efficient in economic and energy consumption terms (see Chapter 3). Conversely, special items –e.g. continuous pasteuriser for ice cream production– must be specifically designed for an optimal operation. In those cases, the most suitable type of equipment is selected, and design variables identified. The resulting process parameters are the solution of the model, that also must fulfil mass and energy balances (Green and Perry, 2008).

G. *Economic Evaluation and Environmental Impact Assessment.* Once the flowsheet design is completed, the financial attractiveness of the process is evaluated. Total capital requirements (cost of equipment, installation, building and land cost, etc) and production costs (cost of raw materials, labour, utilities, management, etc) are estimated. Direct data from manufacturers, specific equipment cost correlations and the Individual Factors method (Peters and Timmerhaus, 2003; Silla, 2003; Sinnot and Towler, 2013) are used in this work for performing the economic evaluation. Most companies have their own factors collected based on their own experience and increase the accuracy of the estimation, but that data is commonly inaccessible. A quantification of CO_2 emissions and water footprint can be also computed based on the process requirements. The carbon footprint is directly related to the different types of energy used within the process, each one having assigned its own Greenhouse Gas Conversion Factor (Coley et al., 2009; Angeles-Martinez et al., 2018), or the leakage of refrigerant gases if applied (Konstantas et al., 2019).

2.7.3. Optimisation in manufacturing systems

Once the entire modelling superstructure is formulated, the simulation of the flowsheet can be carried out. Process simulation can be understood as the problem solving of the system of equations that represents the manufacturing process (Motard et al., 1975). The solution found is however not guaranteed to be the most beneficial.

Optimisation can be defined as finding the best solution of a given system or process within constraints. An objective function is formulated and used as a quality indicator to be minimised or maximised, depending on the aim of the optimisation (Biegler et al., 1997). The decision variables are the problem inputs, used to improve the objective function. The optimal solution will comprise those values of the decision variables giving the best objective function, while meeting the specified constraints (Grossmann, 1996). Typical objectives for process design are minimising operating and capital cost (Niziolek et al., 2016), minimising energy consumption and environmental impact indicators (Ozcan-Deniz and Zhu, 2017), maximising process performance (Tso et al., 2018), or maximising net present value (Zore et al., 2018).

Optimisation techniques can be applied at different levels of the modelling system, from the whole supply chain to specific equipment units. Zamarripa et al. (2013) use multi-objective optimisation for improving decision-making in the supply chain planning. In Martin and Grossmann (2011), the optimisation of the whole flowsheet superstructure is carried out to select the best technology for each unit operation, each comprising an individual optimisation subproblem, based on energy and cost efficiency. Multiperiod optimisation approach is implemented in Martin and Martin (2017), finding the efficient operation of the cooling systems in a power plant, with variable weather conditions. Finally, as an example of individual equipment optimisation, Wang et al. (2018) set the optimal operating pressure of a ternary extractive distillation column, achieving 60% and 50% savings in energy and operating cost respectively.

In this work, multi-objective optimisation techniques are applied for the optimal design of the equipment involving the highest heat transfer within the studied manufacturing processes. More specifically, interior-point is the algorithm used for solving the non-linear multivariable functions within the equipment modelling –e.g. drum dryer in cereal porridge manufacturing or scraped surface heat exchanger in ice cream production. The interior-point approach to constrained minimisation is a sequential (or successive) quadratic programming technique (SQP), suitable for large scale optimisation (Byrd et al., 2000). Sparse linear algebra is prioritised for solving whenever is applicable, and sparsity in data storage is preserved to save memory and hence computational time (Gondzio, 2012). The inherent loss of accuracy linked to interior-point and SQP can be improved by setting low tolerance criteria, providing a solution that can be perfectly assumed for most practical applications (Waltz et al., 2006).

Interior-point method is suitable to solve convex optimisation problems, but it might fail finding a global optimum for nonconvex problems that often have alternative optima (Vanderbei, 1999; Schenk et al., 2007). Nonconvexity can be identified when the optimisation algorithm finds different optimal solutions for alternative initial guesses (Hauer, 2015). To assess and overcome a possible nonconvexity on the minimising function, a multiple shot of initial guesses, i.e. a line space array of starting points within the constrained range, is implemented. The lowest element in the multiple shot solution array is then selected to ensure that the global minimum has been found within the constrained range.

2.7.4. Mathematical principles used in data processing

Here, the mathematical methods used for the analysis of the results obtained by the modelling tool, are described.

2.7.4.1. Change points detection: optimal partitioning algorithm

Characterisation techniques, for the identification of changes in a statistical property – i.e. mean, variance or slope, among others– from a dataset, are commonly implemented in many applications (Killick et al., 2012). Optimal partitioning is a dynamical programming algorithm used for change point detection in signal processing. The data is divided into a defined number of partitions, in which the desired statistical property is estimated (Jackson et al., 2015). A cost function is then defined, firstly computing the deviation of the property from the empirical estimate at each point within a partition, subsequently adding the deviation for all those points, and lastly evaluating the section-to-section deviation. The total residual error is thus computed, and the location of the change point is that partition point giving the minimum total residual error.

Given a signal x_1, x_2, …, x_N, a section empirical estimate χ and a deviation measurement Δ, the algorithm finds an instant k that minimises the cost function $J(k)$:

$$min[J(k)] = min\left[\sum_{i=1}^{k-1} \Delta\left((x_i;\chi([x_1 \dots x_{k-1}])\right) + \sum_{i=k}^{N} \Delta\left((x_i;\chi([x_k \dots x_N])\right)\right] \qquad \text{Eq. 2.2}$$

Depending on the statistical property chosen, the cost function is different (Killick et al., 2012). In this work, the detection of a predefined number of change points, related to the slope of the results dataset, is processed. In that case, the function uses the *Eq.2.3* (MATLAB, 2019a):

$$\big((x_i; \chi([x_m \dots x_n])\big) = (n - m + 1)var([x_m \dots x_n]) - \\ - \frac{\left(\sum_{i=m}^{n}\big(x_i - \mu([x_m \dots x_n])\big)\left(i - \mu([m \;\; m+1 \dots n])\right)\right)^2}{(\mathrm{n} - \mathrm{m} + 1)var([\mathrm{mm} + 1 \cdots \mathrm{n}])} \equiv S_{xx} - \frac{S^2{}_{xt}}{S_{tt}} \qquad \text{Eq. 2.3}$$

This methodology is applied using the built-in MATLAB function '*findchangepts*'.

2.7.4.2. Finite difference method

The finite difference method (FDM) is a numerical method for solving partial and ordinary differential equations. FDM approximates the value of a derivative function of any order by discretisation (Zhou, 1993). For example, following the Taylor's theorem with a central-difference approximation, the first derivative of a single valued, finite and continuous function, can be approximated as follows (Smith, 1985):

$$\left.\frac{d\,f}{dx}\right|_{x=x_0} = \frac{f(x_0 + h) - f(x_0 - h)}{2\,h} + \mathrm{O}(h^2) \qquad \text{Eq. 2.4}$$

Where f is the evaluated function, x_0 is the local point where the derivative is approximated, h is the uniform grid spacing, and $\mathrm{O}(h^2)$ denotes the second order error between the approach and the real value. To minimise the discretization error and increase accuracy, the grid spacing can be shortened. Fornberg (1988) developed an algorithm that generates the finite different weights, for a difference approximation with uniform grid spacing of any order of derivative and to any order of accuracy. *Eq 2.5* shows the central-difference approximation of the first derivative, with a fourth order of accuracy.

$$\left.\frac{df}{dx}\right|_{x=x_0} = \frac{-\frac{1}{12}f(x_0+2h)+\frac{2}{3}f(x_0+h)-\frac{2}{3}f(x_0-h)+\frac{1}{12}f(x_0-2h)}{h}+O(h^4) \qquad \text{Eq 2.5}$$

FDM can approximate the value of the slope of the tangent at any point in a set of data. Central-difference approximation should be therefore used. An algorithm for the implementation of FDM has been built in MATLAB. It reformulates Fornberg's formula into a system of linear equations, which solution is the finite different coefficients vector. The designed function is then used to compute the first and second derivative at each point. The point where a plateau is reached in a set of data –i.e. the first derivative is zero– can be identified, when the defined tolerance criterion is met.

2.7.4.3. Least-Squares Fitting.

In this work, the least-squares methodology is used for fitting experimental and generated data to a specific parametric model. The objective is the estimation of the model coefficients that best relate the response data to the predicted one. For that purpose, the best solution is the one that minimises the sum of the squared residuals, i.e. a residual being the difference between the actual value and the predicted output. In a data set of n pair of points (x_i, y_i), i = 1, … , n, where x_i is an independent variable and y_i is the dependent variable, the objective function R to minimise for an accurate fitting is (Marquardt, 1963):

$$min[R] = min\left[\sum_{i=1}^{n}(r_i)^2\right] = min\left[\sum_{i=1}^{n}(y_i-\hat{y}_i)^2\right] \qquad \text{Eq 2.6}$$

$$min[R] = min\left[\sum_{i=1}^{n}\left(y_i - f(x_i,\boldsymbol{\theta})\right)^2\right] \qquad \text{Eq 2.7}$$

Where $\hat{y}_i$ is the predicted value of the dependent variable, r_i is the residual, $\boldsymbol{\theta}$ is the vector comprising the population of k parameters ($\theta_1, \ldots, \theta_k$), and f is the model function that predicts the value of the dependent variable.

In this work, f will be either a linear function or a non-linear function. For the former cases, the linear least squares method is applied and solved using the '*lsqlin*' function in MATLAB. Nonlinear least squares fitting is computed by the '*lsqnonlin*' MATLAB function, based on Levenberg-Marquardt and trust-region-reflective methods (MATLAB, 2019b).

2.8. Conclusions and main objective of this work

This literature review has first shown the evolution of manufacturing systems. It has shown a continuous shifting process seeking to fulfil existing needs at each era until the present time. The current changes in the manufacturing scenario has been subsequently described, and the main drivers that motivate this shift noted. This led to identifying the current debate between centralised and decentralised manufacturing systems.

Many theoretical approaches, suggesting a shift of manufacturing systems to a decentralised scheme (e.g. Distributed Manufacturing), adapting to an increasingly competitive market dominated by consumer wishes, have been developed. However, there is a lack of empirical work and tools analysing the trade-offs between the two disputing methods competing to shape the new manufacturing paradigm. Of all industrial sectors, the food industry has been chosen due to the increasing demand of food production and its great ratio in economic, energy and environmental impact shares.

This work proposes a model-based methodology to design, evaluate and compare, both in economic, energy use and environmental terms, the profitability of different food manufacturing scenarios across a wide range of production scales and decentralization alternatives –from domestic kitchen production to a single high-volume processing plant. The objective is to use process system engineering techniques to design different scenarios and generate the most accurate data possible. PSE methods have shown a proven beneficial impact in economic, social and environmental terms when applied to chemical processes. However, they have not been extensively applied in the literature.

The output of this study will be a modelling toolbox that will help companies in the complex decision between centralized manufacturing or decentralized manufacturing systems. Three different food product cases studies are developed –i.e. sandwich bread, cereal baby porridge and ice cream– comprising contrasting features, and the variable applicability of these methods will be therefore assessed. Ultimately, the common perception that local food production involves more expenses is thus challenged.

Chapter 3

Dry Cereal Baby Porridge

The following chapter has been published in Sustainable Production and Consumption, Volume 19 (Almena et al., 2019a)

Awarded the ***Hutchison Medal 2020*** by the Institution of Chemical Engineers (IChemE)

The part regarding the optimisation of the drum dryer operation has been published in Energy Procedia, Volume 161 (Almena et al., 2019c).

The modelling and simulation work, and the development of the ideas was carried out by myself along with the writing of the papers. Estefania Lopez-Quiroga reviewed the structure and provided correction to the grammar and spelling. Serafim Bakalis and Peter Fryer provided guidance and supervision during the research and writing/correction of the paper. Each paper has been reviewed by two anonymous reviewers prior to publication.

3.1. 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 involves rigid and lengthy supply chains with high 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 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, when equal power source are used, decentralized manufacture does not imply saving in energy or greenhouse gases emissions (GHG) but demand more manpower.

3.2. 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 (Helpman, 1981; Hu, 2013). Large-scale production led to a standardisation of the product and – lengthy (Srai et al., 2016a) – 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 (Garrehy, 2014) and significant costs (Mourtzis and Doukas, 2012) 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 (Harrison et al., 2018), and in this way satisfy the eco-demand of modern societies (Angeles-Martinez et al., 2018). 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 (Mourtzis and Doukas, 2012) - represents a promising alternative to many of CM drawbacks. Modular Manufacturing (Baldea et al., 2017) and Additive Manufacturing (Hannibal and Knight, 2018), both based on decentralised systems, can be mentioned as emerging examples of this shift on manufacturing methodologies.

It was already assessed in Chapter 2 how the Food Industry, which is the largest sector in the UK contributing £121 billion (6.4%) to the Gross Value Added (DEFRA, 2019a), 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) (DEFRA, 2017). Therefore, the search for alternative manufacturing methods that help to decrease environmental burdens is critical also for the Food sector. Distributed Manufacturing (DM), based on decentralised small-scale production and location close to customers (Cottee, 2014; Srai et al., 2016a) has been 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 (Sellitto et al., 2018) - for example, implementing DM as the production stage of Short Food Supply Chains (Sage, 2003) has the potential to lead to 'good food network' (Matt et al., 2015). 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 (Srai et al., 2016a). A schematic representation of centralised and distributed manufacturing systems was shown in *Fig.2.7*.

In this framework, a novel model-based methodology is presented for the analysis and comparison of these different manufacturing scenarios. It 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 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 basis of this methodology will be illustrated using a dry food product (dry cereal porridge, reconstitutable with the addition of water or milk and suitable for baby feeding). 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). The impact of energy use at the manufacturing stage is even greater for baby porridge. The low levels of pancreatic amylase found on babies' organism, i.e. the enzyme responsible in the human body for breaking starch molecules (Schiess et al., 2010; Lin and Nichols, 2017), advises to make an easy digestive food product. Previous studies have shown that the rate of absorption of gelatinized starch by amylase is several times greater than that of native starch (Shujun Wang et al., 2016). Therefore, a processing stage that involves water addition and heating to perform starch gelatinization, that must be later evaporated at the drying unit, is introduced in the manufacturing process.

Conversely, transportation and storage are cheap for this type of products. 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.

3.3. Characterisation of different manufacturing scenarios

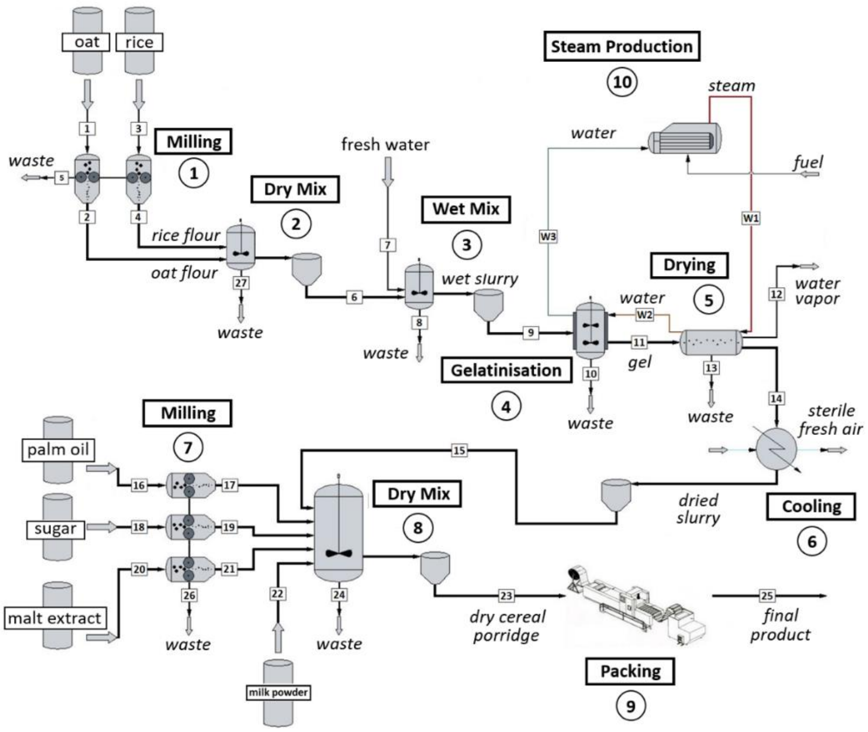
3.3.1. General description of the manufacture process

Two different manufacturing methods are considered in this work: industrial and artisanal production. *Table 3.1* lists the most representative production conditions and equipment for each case. Industrial production is based on a process line (*Fig.3.1(a)*), whilst Artisan production keeps the same unit operations but at smaller scales. This requires changes in the equipment (see *Fig.3.1(b)*) and other manufacturing aspects, e.g. batch operation. Further equipment details (e.g. prices, dimensions, capacities) are provided in the Appendix A (see *Table A.1*, *Table A.2* and *Table A.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.

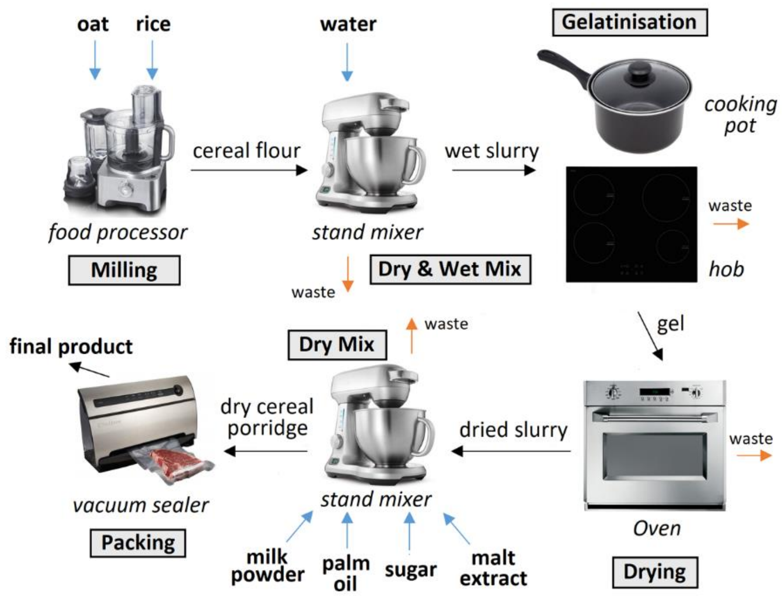
3.3.1.1. Industrial manufacturing process

The industrial manufacturing process for baby cereal porridge manufacturing –*Fig.3.1(a)*– is described in the following lines. Cereals −rice and oat− arrive at the plant to be grinded. Cage mills are the chosen units for this purpose, being considered the optimal ones for achieving cereal grains milling with a negligible residence time (Marcotte, E., 2015). After grinding, both flours are mixed in a double cone blender on sterile atmosphere for 15 min −optimal solid-solid and solid-liquid mixing time (Green and Perry, 2008). Next, water and flours are mixed in a ribbon blender, leading to homogenous wet slurry with moisture content up to 80 w%, the best condition for cereal's starch gelatinization (The Quaker Oats Company, 1984). Clumping or lumping of the flour into water is avoided by mixing at room temperature with continuous agitation. Then, the wet slurry is driven to a jacketed stirred tank where the gelatinization of starch happens. Heat supply is required due to the endothermic nature of the reaction, so that flowing hot water would be the heat source. Although each cereal has its own gelatinization temperature, and the processed flour is comprised of oat and rice with starch gelatinization temperatures of conclusion of 68.6 °C (Ovando-Martinez, M. et al, 2013) and 78.8 °C (Bao, J. et al, 2013) respectively, the mixture must be heated up over the top gelatinization temperature to decrease the viscosity of the gel and improve drying efficiency. Thus, a temperature of 88 °C and atmospheric pressure are the optimal operation conditions set for this stage. The gelatinization takes place during time of 20 min with a continuous agitation of the gel (The Quaker Oats Company, 1984).



(a)

Figure 3.1. (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 3.1. (b) Artisanal manufacture flow chart. The industrial unit operations are adapted to be developed as a domestic kitchen batch process.

Later, the following step is the drying of the wet slurry in a double drum dryer, providing flakes shape to the product. The dryer works at atmospheric pressure using steam, generated in the own plant, as heat supply. The dried slurry output is cooled down to atmospheric temperature while it is transported to the next unit, using a belt conveyor with conditioned air for this purpose. Meanwhile, the rest of the ingredients are milled to achieve a low particle size and stored for being ready to use, except for milk powder that is directly added. All the additives and the dried slurry are subsequently mixed at the fixed composition in a second double cone blender. Finally, the product is ready for packaging and commercial selling.

3.3.1.2. Artisanal production process

Although artisanal processes keep the same unit operations than industrial ones, smaller scales of production demand some changes to the manufacturing process, e.g. raw materials will be purchased in retailers rather than to wholesalers with an increase in their price. The artisanal process is a batch process, contrasting with the continuous operation of the plant processing. A food processor will be used for milling, a stand mixer for wet and dry mixing stages, a cooking pot for gelatinization (cooking), a convection domestic oven for drying and vacuum sealer for packing. Describing the batch process, first, both cereals are milled in a food processor. Milling the cereal crops using this instrument would require more time than the industrial cage mill, so 5 min are taken for this stage. Then, the grounded cereals are mixed with water –added up to a 80 w%– in the stand mixer for 15 min, same time slot than the industrial process. Dry and Wet mixing are carried out at the same time due to the small size of the batches. The following step is the gelatinization, taking place in a pot heated by an induction hob. After cooking the wet slurry, the resulting gel is dried in the domestic convection oven until the desired water content is achieved. Once the cereal slurry is dried, the rest of the ingredients are mixed in an additional stand mixer. Finally, the finished product is packed in pouches using a vacuum sealer before commercialising, taking half a minute for the sealing of each bag.

Table 3.1. Unit operations, operating conditions and equipment used for industrial and artisanal dry cereal porridge manufacturing processes.

		Equipment	
Unit Operation	Main Conditions	Industrial Production (*Fig. 3.1(a)*)	Artisanal Production (*Fig. 3.1(b)*)
Milling	5 min (Marcotte, 2015)	Cage mill	Food processor
Dry mixing (1)	15 min (Green and Perry, 2008) Sterile atmosphere (industrial)	Double Cone Blender	Stand Mixer
Wet mixing	Moisture content up to 80 w% (The Quaker Oats Company, 1984)	Ribbon Blender	Stand Mixer
Gelatinisation	T = 88 °C (Ovando-Martinez et al., 2013) 20 min (Bao et al., 2006)	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 (Green and Perry, 2008) Sterile atmosphere (industrial)	Double Cone Blender	Stand Mixer
Packing	30s/pouch	Automatic Packing Machine	Vacuum Sealer

3.3.2. Production scenarios

Four different scenarios for the production of dry cereal porridge were considered, from extreme distribution to centralization, as depicted in *Fig.3.2*:

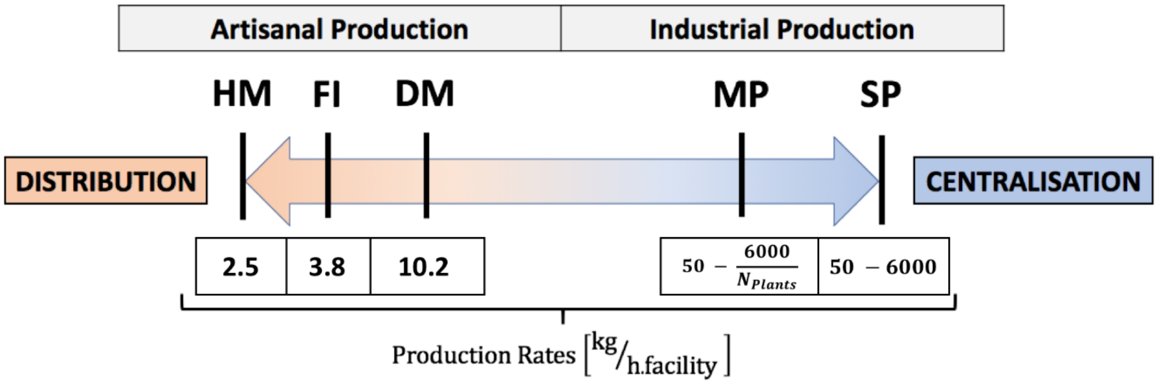


Figure 3.2. Schematics representing the production methods and scales considered in this work. HM: Home Manufacturing, FI: Food Incubator, DM: Distributed Manufacture, SP: Single Plant, MP: Multiple Plant. The production rate numbers respond to the manufacturing scales designed on this case study. N_{Plants} is the chosen number of factories comprising the multi-plant net.

(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.

(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 of them– designed to satisfy product demand.

3.4. 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 input parameters, 2500 equations and has been implemented in MATLAB®. *Fig.3.3* depicts the sequence the modelling platform follows to solve the model.

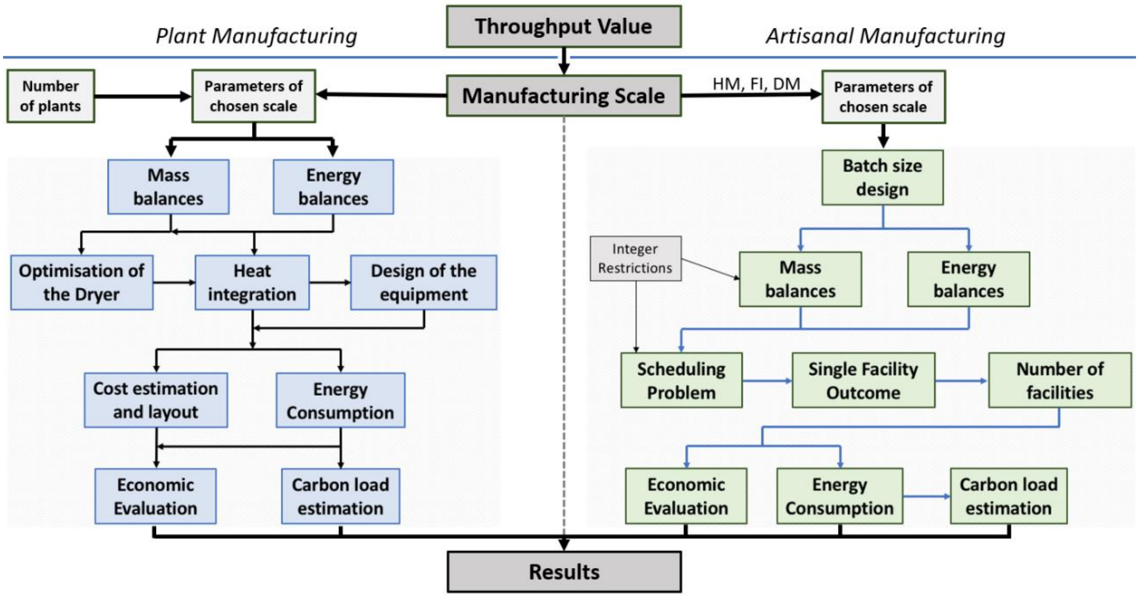


Figure 3.3. Flow diagram representing the sequential process to build and solve the modelling of cereal porridge manufacturing scales.

3.4.1. Model assumptions

3.4.1.1. 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 as an approach to account material losses within those units.

- Greenhouse gas emission (GHG) are estimated from calculated energy demand using the corresponding energy conversion factors (Government of 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 A.12* in the Appendix A for values).
- The selling format is baby food pouches of 0.2 kg.

3.4.1.2. 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 Engineering 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.

3.4.1.3. 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 30 s per sealed pouch –see *Table 3.1*.
- 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 x 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 (from 1 to four ovens per facility).
- 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 kinds of ovens are studied: electric and gas.

- No labour 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).
- HM has no building cost associated as the activity is developed in 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 20 m^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.

3.4.2. 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 those process units that operate in continuous (e.g. drum dryer). Conversely, the amount of materials that enter batch equipment (e.g. stand mixer) is processed during the set residence time –see *Table 3.1*. When treatment has finished, the total mass is sent to the next stage. Eq.3.1 and Eq.3.2 correspond to the global and component i mass balances, respectively, for J inlet and K outlet streams.

$$\sum_{In} \dot{M}_J - \sum_{Out} \dot{M}_K = \dot{M}_{Accum} + \dot{M}_{Waste} \quad 3.1$$

$$\sum_{In} \dot{M}_J * x_i - \sum_{Out} \dot{M}_K * x_i = \dot{M}_{Accum} * x_i + \dot{M}_{Waste} * x_i \quad 3.2$$

where $\dot{M}_J, \dot{M}_K$ are mass fluxes (kg/s) and x_i (w/w) are mass fractions. J and K stream indexes run from 1 to 30 (number of streams), while the number of ingredients accounted is seven (i = 1:7).

As thermal processes are involved in manufacturing (i.e. gelatinization, cooling, drying and steam production), energy balances are performed to evaluate heat needs. The total energy required by each thermal process is calculated as the sum of the corresponding sensible and latent heats, as defined by Eq.3.3:

$$\dot{Q}_{tot} = \dot{Q}_{sensible} + \dot{Q}_{latent} = \dot{M} * Cp_j * \Delta T + \dot{M} * \Delta H^{evap} \qquad 3.3$$

$$\mathrm{Cp}_{\mathrm{prod}} = \sum_{i}^{n} \mathrm{x}_i * \mathrm{Cp}_i \qquad 3.4$$

where $\mathrm{Cp}_{\mathrm{prod}}, \mathrm{Cp}_i$ (J/kgK) are specific heats of the product and single components respectively, ΔT 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).

3.4.3. Drying operations

The drying step demands around 86% of the heat supplied for the entire manufacture process according to the energy balance results. 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 (Sinnot and Towler, 2013). 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 Appendix A (*Section A.3*) and Appendix B (*Section B.5*).

The operation of the convective oven was described in 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 Appendix A *(Section A.4*).

3.4.4. Cost estimation

Economic evaluation at plant scale has been carried out with a first estimation of the total annual production cost and total capital.The Individual Factors method has been implemented for this purpose (Peters and Timmerhaus, 2003; Silla, 2003; Sinnot and Towler, 2013). The factors used are shown in *Table A.7* and *Table A.8* in the Appendix A.

3.4.4.1. 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. Equipment purchase and installation is estimated using correlations from Matches' Process Equipment Cost Estimates database (Matches, 2014), and installation factors (see *Table A.1* and *Table A.9* in the Appendix A).

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.

3.4.4.2. 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 A.10* (industrial method) and *Table A.11* (artisanal method) in the Appendix A. Energy prices are also in the Appendix A (see *Table A.12*). Labor cost, equipment depreciation and management cost are not computed using individual factors.

3.4.4.3. Labour cost and equipment depreciation

An organization chart is developed showing direct and indirect labor for the plant (see *Fig.A.1* in the Appendix A) and DM (see *Fig.A.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.

3.4.4.4. 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% over the baby cereal porridge sales revenue (Huet, 2015). The seller is responsible for the quality and hygiene of the product, following food hygiene regulations. Part of the management fee would be used to meet the food quality and safety standards, and to develop new techniques and products. Management cost at DM and SP/MP scales comprises different items (see *Table A.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 –i.e. a corporation model. 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 *Fig.A.2*).

3.4.5. Net profit calculation

The Net Profit per facility (${\Pi_{bf}}^{fac}$) is calculated from Eq.3.5. 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 19 % of the Gross Profit (Government of United Kingdom, 2019b).

$$\Pi_{bf}{}^{fac} = \left(1 - \frac{\%Tax_{corp.}}{100}\right)\left[\left(1 - \frac{\%VAT_{bf}}{100}\right)\left(q_{bf}\, p_{bf} - C_{bf}\right)\right] \times \left(\frac{1}{N_{facilities}}\right) \qquad 3.5$$

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 is the benefit for the holder owning one branch comprising the net of facilities that develops the food production.

3.5. Results and discussion

The designed tool generates data for different scenarios. For each, it provides cost estimation, design of equipment, number of facilities and labour requirements, 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 analysed to find points that imply trend variations, such as the highest change on slope (HCS) or the plateau reaching point (PR). It is assumed 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 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, the model is employed to assess a case analogous to the UK framework, analysing how decentralized methods for the production of dry cereal porridge would supply the entire UK demand.

3.5.1. Effect of the production scale on the operating cost

The production rate is defined as a variable. *Fig.3.4* shows unit costs for each production scenario as a function of the production rate (kg/h). Profitable scenarios provides unit costs below the average market price of the product –e.g. 10$/kg in the UK (Tesco, 2017). 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 *Fig.3.4*. 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 *Fig.3.4* is addressed in Section 3.5.2.

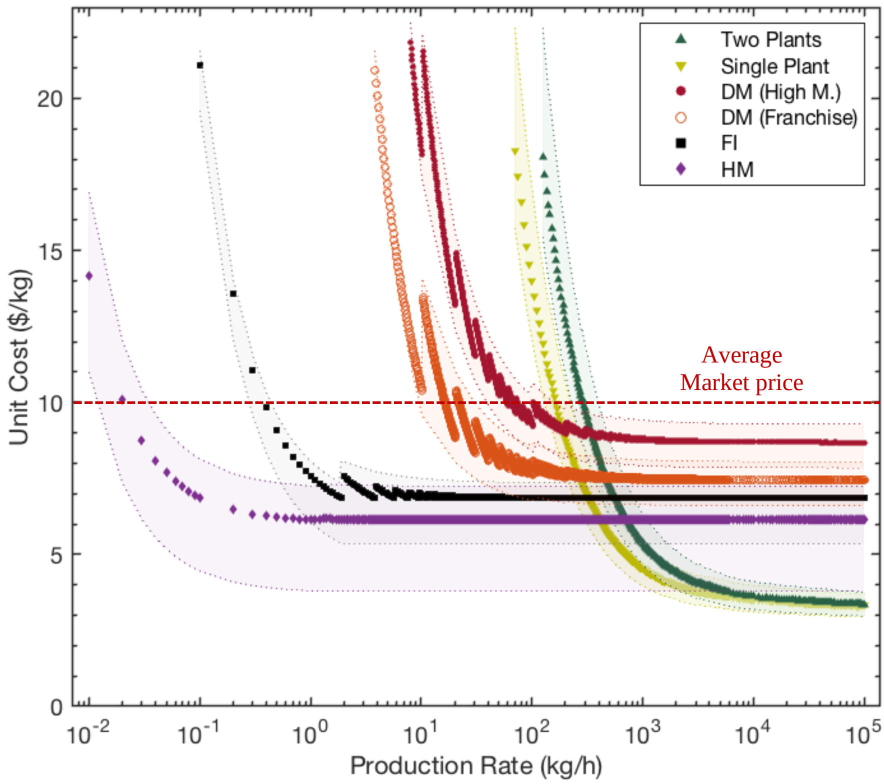


Figure 3.4. Variation of the unitary cost with porridge throughput for different production scales. Unitary costs above 10 $/kg (assuming UK market prices) incur in economic loss and thus result in non-profitable production scenarios. According to this, SP is not profitable for throughputs below 200 kg/h; DM range of operation is profitable above 60 kg/h (corporation - high management) and 20 kg/h (franchise - low management); HM and FI result in unitary costs below the 10$/kg profitability bound even at very low production rates.

3.5.1.1. Breakdown of the unit cost

The operating cost per unit has been broken down and analysed. 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 labour, 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 re- quired, 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 *Fig.3.4.* 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. The more expensive fixed cost assigned to MP shift the curves to the right, while variable costs contribution remains the same.

3.5.1.2. 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 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 3.2 shows the crossover points for HM, FI and DM plots with the SP & MP curves displayed in *Fig.3.4*, including uncertainty bounds. Those points suggest where the artisan manufacturing scales become more cost-effective than industrial scenarios:

Table 3.2. Crossover points from *Fig.3.4* 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 (unitary cost – $/kg).

Throughput (kg/h) Unitary 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

- 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.
- 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.

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

The methodology described in Section 3.5 was applied to the data of *Fig.3.4.* For each manufacturing scale curve, HCS and PR points were computed. *Fig.3.5* compares one example of artisan manufacture (i.e. DM at low management) to one of industrial manufacturing (SP).

HCS and the PR points divide the data in three recognizable regions. The left section comprises the region 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.

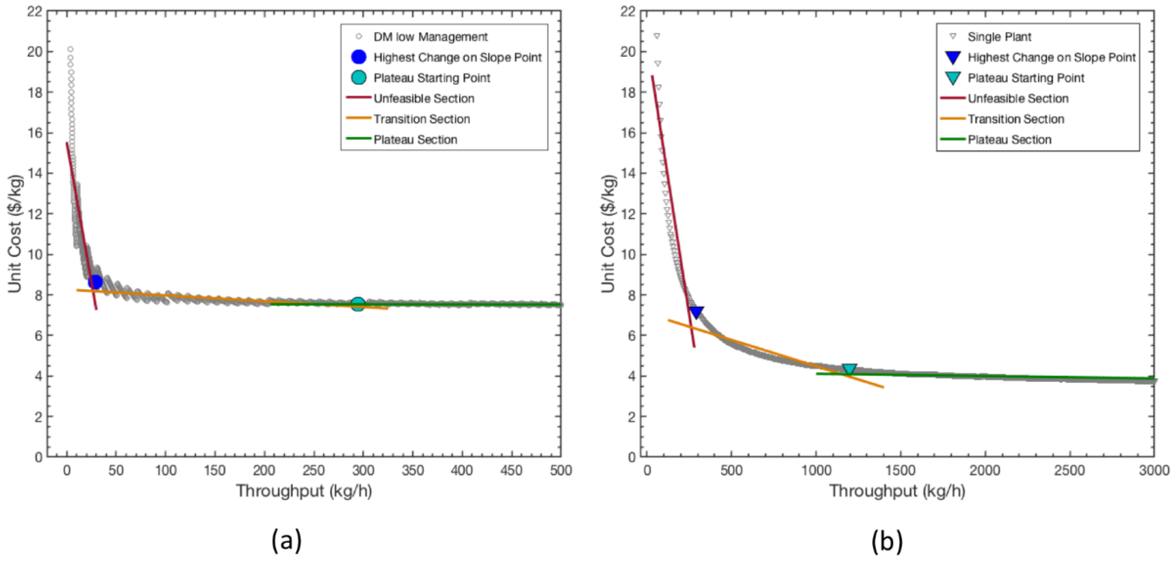


Figure 3.5. Example of how the different operation regions for a manufacturing scale are identified: Graphs show (a) DM low Management and (b) Single Plant scenarios. Dark blue marks (dots for (a) and triangles for (b)) represent the biggest change on slope, while light blue ones indicate the plateau 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.

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 3.3*. 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 3.3. High change on slope (HCS) and plateau reaching (PR) points for each porridge manufacturing scale. X-axis coordinate (throughput – kg/h) and y-axis coordinate (unitary 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 *Fig.3.5*.

	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 e-07	6.13
FI	-27.75	21.25	0.5 9.07	-0.011	7.14	32 6.87	-2.63 e-06	6.86
DM (Low M.)	-0.28	15.53	28.5 8.65	-0.003	8.26	291 7.57	-4.80 e-05	7.55
DM (High M.)	-0.21	19.29	49.2 10.41	-0.002	9.67	557 8.8	-6.96 e-05	8.86
SP	-0.05	20.45	290.0 7.21	-0.003	7.08	1195 4.35	-9.17 e-05	4.23
2P	-0.08	30.62	295.0 9.88	-0.003	8.87	1520 4.70	-9.77 e-05	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 behaviour. 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 that can be taken from this methodology is the length of the transition region for each manufacturing scale. Industrial manufacturing (see *Fig.3.5(b)*) shows the longest section, showing the effect of the economy of scale.

3.5.3. Effect of manufacturing scale on total capital

Total Capital was 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 *Fig.3.6(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.

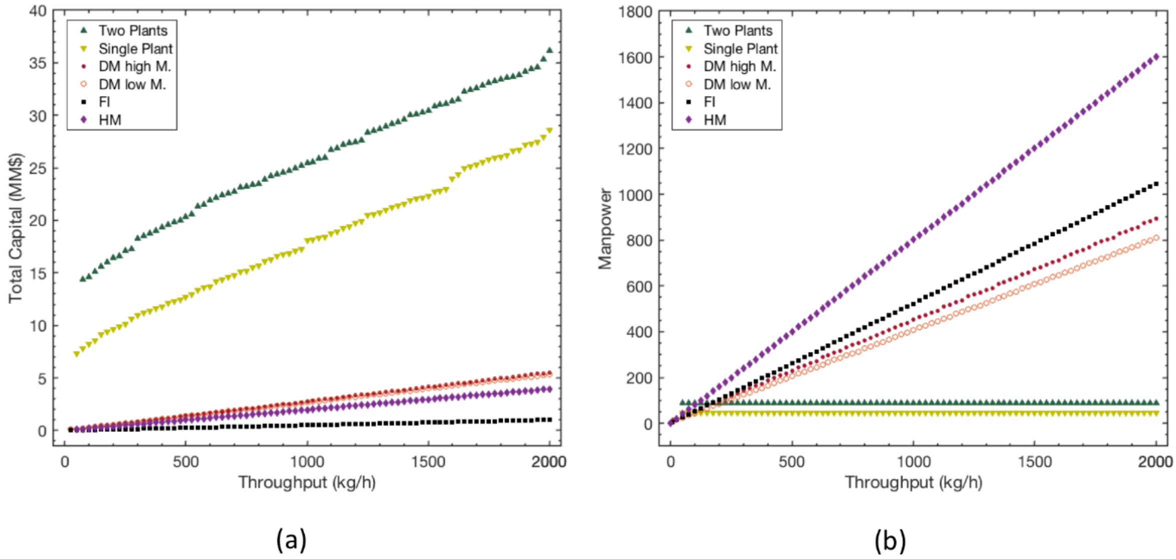


Figure 3.6. (a) Total capital and (b) Manpower required for each production scale at different final product´s production rates. Industrial manufacture requires a much larger investment than artisanal production scales, as depicted in (a). Furthermore, the greater number of facilities for small scales 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.

Fig.3.6(b) show the manpower needed at each production rate. Industrial manufacturing labour 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. However, being representative of 'gig-economy', labour 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. Labour cost becomes even greater for those scenarios that include more management personnel.

3.5.4. 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 was estimated as a 5% of the total demand (Minister of Agriculture and Agri-food Canada, 2012). 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 for an industrial single plant supplying the entire UK demand, together with specifications of the comprising equipment, are listed in *Table A.13* and *Table A.14* of Appendix A respectively.

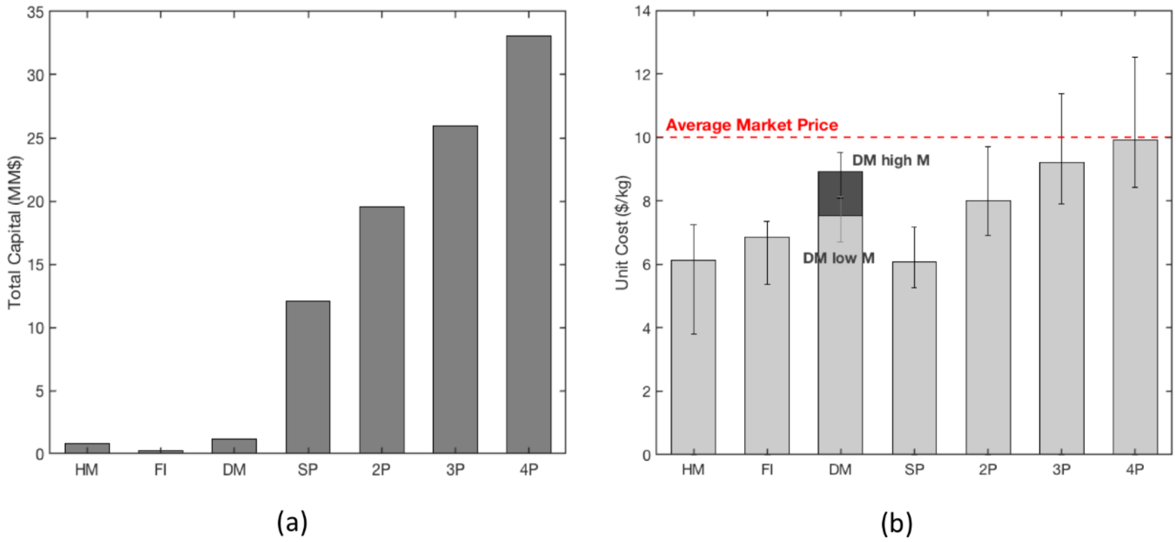


Figure 3.7. Total capital (a) and unitary operating cost (b) for HM, FI, DM, SP and MP production scenarios under UK dry baby food demand (418 kg/h). In (b) DM has two unitary operating cost values for high management (dark bar section and franchise (light bar section). Error bars show the uncertainties 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. Unitary 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.

3.5.4.1. Total Capital

Total capital corresponding to each UK-based scenario is presented in *Fig.3.7(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%).

3.5.4.2. Unit operating cost

The production cost for each scale (1 kg of final product as basis) is presented in *Fig.3.7(b)*. The average selling price of dry baby cereal porridge – found in UK supermarkets (Tesco, 2017) –is ca. 10 $/kg. The production cost must be below this to achieve profitability. Results show that HM (6.13 $/kg) and FI (6.86 $/kg) are the scenarios with the lowest production cost using artisanal manufacture. The impact of the labour cost paid and the high management cost as a result of moving from 'gig-economy' to Distributed Manufacturing, increases the cost. 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. Conversely, using two plants to supply the UK demand appears cheaper than the DM scenario for high management conditions.

3.5.4.3. 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 were calculated. 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).

3.5.4.4. Energy demand and carbon footprint at manufacture stage

Table 3.4 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).

Table 3.4. Carbon Footprint of HM, FI, DM, SP and MP (two plants) at the manufacturing stage for cereal porridge. Artisanal production scales show results for both electric and natural gas oven cases.

Manufacturing Scenario	Total Energy	Electricity Consumption	Fuel Consumption	CL_{Elect}	CL_{fuel}	CL_{Total}
	kJ/kg	kWh/kg	kg/h		$kg\ CO_{2_e}/kg$	
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

The carbon footprint for each scenario was estimated from calculated energy values using the UK Government Greenhouse Gas (GHG) Conversion Factors (Government of 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 3.4*. 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%.

3.6. Overview: 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' (labour 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 customers 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 et al., 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., 2016a). 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. Localization 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, 2001).

3.7. Conclusion

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 five 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 decentralised 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.

Chapter 4

Sandwich bread

Some of the results within this chapter have been previously published in Energy Procedia, Volume 161 (Almena et al., 2019b).

4.1. Introduction

Bread is a basic food that has played an important role in the human diet throughout history. It dates back to the Neolithic era –ca. 12,000 year ago– as a result of experiments with water and grain flour (Mondal and Datta, 2008). It became a staple when humans switched from hunter-gatherers to farmer lifestyle (Marchant et al., 2008). Bread delivers both satiety and nutrition (Wang, 2015). In all its forms, it is the most consumed food worldwide, at around 70 kg of bread per capita per year (De Boni et al., 2019).

Most breads can be considered semi-perishable foods (Ravimannan et al., 2016). Immediate refrigeration is not needed for preservation, but shelf life is limited to around 4-7 days unless frozen. However, it is generally best consumed when fresh (Dal Bello et al., 2007). A fast drop in quality is caused by staling, a quite complex spoiling mechanism, mainly caused by water migration phenomena and starch polymer retrogradation, that happens during storage (Gray and Bemiller, 2003; Monteau et al., 2017). Losses in both sensory –loss of aroma, mouth feel– and physical –increased crumb firmness, crust softening– quality make ‘stale bread’ less acceptable to the consumer (Hebeda and Zobel, 1996; Gellynck et al., 2009; Zhang et al., 2017). Bread staling causes great economic losses to the baking industry (Gray and Bemiller, 2003). Retardation of staling to improve bread shelf life is therefore a concern for industrial bread making. Additives, e.g. amylolytic enzymes, are incorporated to the product recipe (Giménez et al., 2007), thus compromising the naturalness of the product.

Commercial bread baking is an important sector in the food industry, with more than 94 million tonnes of bread annually consumed worldwide (Khatir et al., 2015). The UK bakery market has an annual income of £3.6 billion (FoB, 2016). Large energy use and environmental impact are associated with this sector, for example bread making annually consumes 2 TWh and causes 570,000 tonnes of CO_2 emissions in the UK (Paton et al., 2013). Approximately 75% of UK bread is manufactured in large commercial bakeries at industrial scale, while the rest is locally produced (FoB, 2016). Small-volume baking businesses are common to satisfy customers that demand fresh and high-quality bread (Salim et al., 2020). Around one third of the small and medium sized enterprises in the UK are manufacturers of baking products, which shows the great importance of the sector in entrepreneurship (Government of United Kingdom, 2019d). The ratio of locally/industrial manufactured bread, however, strongly depends on the country of study and their tradition. For example, in Spain 81.9 % of the consumed bread is freshly baked, while only 18.1% is industrially manufactured (Mercasa, 2018).

This work focuses on the UK scenario. López-Aviles et al. (2019) suggest that changing the UK bakery sector situation to distributed manufacturing, based on medium-small scale bread production, might increase energy use and environmental impact. They also conclude that this scenario is not clear. The impact of transportation in considering the bread supply chain implies that savings could be achieved by local bread production. To shed light on the first hypothesis, the methodology developed in this thesis is applied to bread making. Again, five manufacturing scenarios with different degree of decentralisation –i.e. HM, FI, DM, SP and MP– are designed for bread production. All the scales are compared in terms of economic feasibility, energy consumption and environmental impact.

There are a wide variety of bread products. For simplicity, this chapter will consider sliced bread loaves, i.e. sandwich bread, as the representative product. Sandwich bread is manufactured in both industrial and local bakeries and extensively sold within the UK. Most bread products share the same manufacturing process for different product recipes, baking time, temperature and final product's weight, so the model could be extended to other bread products.

4.2. Product formulation

The main ingredients of bread dough are cereal flour, water, salt and yeast (Gisslen, 2016). The diversity in loaf formats creates a wide variety of recipes (Verdú et al., 2017; De Boni et al., 2019; Corocho et al., 2020). Here, a conventional bread formula –see *Table 4.1*– is chosen as the benchmark case (Campbell et al., 1993). Alternative formulas, i.e. part baked and frozen bread (PBFB) and French bread formulas also listed in *Table 4.1*, are considered in sensitivity analysis to prove the modelling tool flexibility. No additives for longer shelf life are considered in this work.

Table 4.1. Formulation of dough for three different recipes: conventional bread (Campbell et al., 1993), part baked and frozen bread (Le-bail et al., 2010) and French bread (Purlis, 2011).

Ingredients (x_i)	Conventional bread	Part baked and frozen bread	French bread
Wheat flour	0.601	0.637	0.625
Water	0.367	0.331	0.338
Salt	0.011	0.013	0.010
Yeast	0.015	0.013	0.007
Improver	0.006	0.006	-
Sugar	-	-	0.010
Margarine	-	-	0.010

4.3. Design of the alternative manufacturing processes

The concept developed in the previous chapter to represent production methods with different manufacturing scales, is applied here. Industrial and artisanal production methods are described below, both comprising the same set of unit operations. Bread production consists of: (1) Mixing of raw materials, (2) Dough division, (3) Dough moulding, (4) Proofing, (5) Baking, (6) Cooling, (7) Slicing and (8) Packing.

4.3.1. Industrial bread making

Mass production of baking products is carried out in continuous mode (Tsarouhas, 2009). An automated bread processing line has been designed for industrial bread manufacturing (Tsarouhas and Arvanitoyannis, 2010). *Fig.4.1* shows the flowchart of the process, while *Table 4.2* lists common equipment used to perform each unit operation, together and the main operation conditions. Transportation between units is mechanical.

Raw materials, at the composition set in the product formulation, are firstly driven into a two-speed gear ribbon blender. Two different processes, pre-mixing and kneading, take place in this device. Lower agitation is required to pre-mix the ingredients, while the speed is doubled during kneading. The batch is then loaded into a funnel, where a divider splits the dough into individual pieces of the selected weight. The dough pieces are subsequently moulded in a two-step process. A Teflon conical rounder first submits the dough portions to a helical ascending movement that rounds and coats the dough with flour (Probake, 2019). The appropriate loaf-shape is achieved in the second moulding using a bread maker. Dough loaves are then placed individually in baking pans.

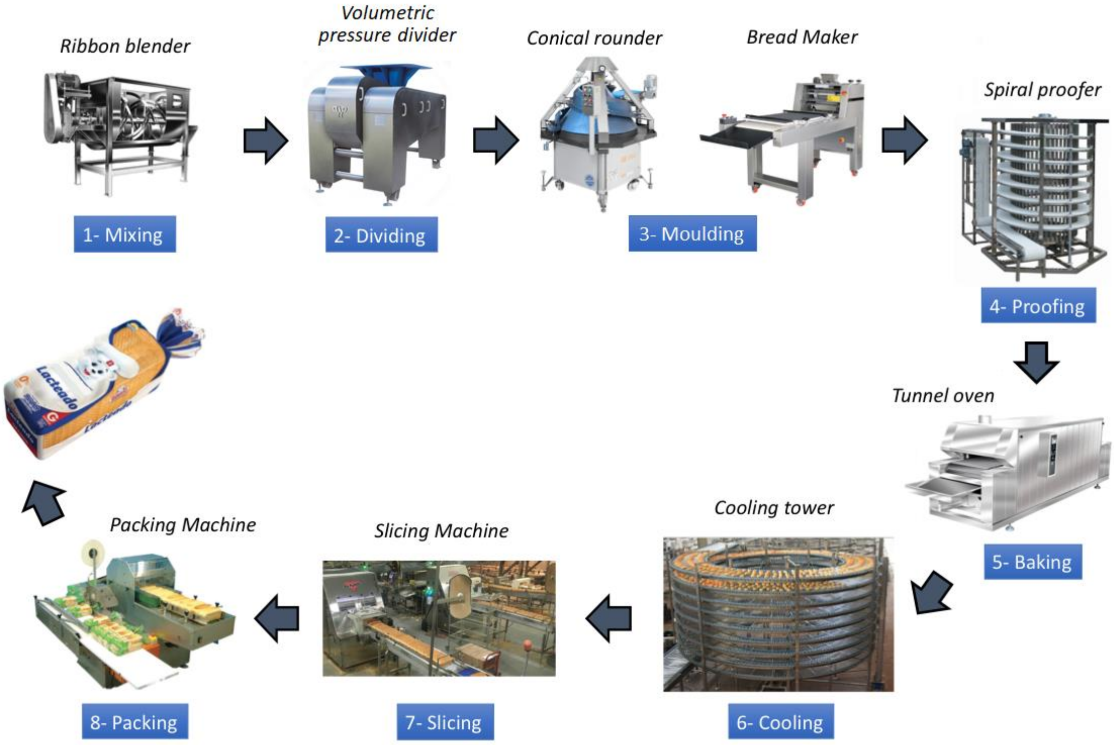


Figure 4.1. Industrial flow chart for bread manufacturing in a processing plant.

After moulding, a continuous proving takes place in the spiral proofer. Temperature, humidity and residence time are adjusted to allow optimal fermentation of the dough (Scanico, 2019). A conveyor then loads the proofed bread into a tunnel oven, where baking takes place. This is an enclosed long chamber with different heating sections, that contain gas burners or electric heating, to achieve the desired temperature profile for baking (Davidson, 2016). Next, the baked products are cooled in a continuous spiral cooler, whose speed is set to allow time enough for the bread to reach ambient temperature (The Henry Group, 2019). The loaves are later sliced and packaged individually. Finally, the product is ready to be stored and distributed.

Table 4.2. List of the unit operations, operating conditions and equipment comprising a continuous industrial processing line for bread making.

Operation	Unit	Residence time	Main Conditions
Storage: raw mat.	Silos	30-day supply	$T_{ambient} = 20^{\circ}C$ Dry conditions
Mixing:	Ribbon blender		
i) premix		2-5 min	100 – 150 rpm
ii) kneading		7-10 min	300 – 360 rpm
Dough division	Volumetric pressure divider	< 1 min	$T_{ambient} = 20^{\circ}C$
Dough moulding	Conical rounder Bread machine	1 min 3 min	$T_{ambient} = 20^{\circ}C$
Proofing	Spiral prover	60 min Or 8 + 50 min	T_{proof} =32-42 ˚C 70 % hr
Other ingredients adding	Seeds Sprinkler	< 1 min	Ambient
Baking	Tunnel Oven	25 min	230-260 ˚C Steam 0.5kg/kg bread
Cooling	Cooling tower	120 min	$T_{ambient} = 20^{\circ}C$
Slicing	Slicing machine	< 1 min	$T_{ambient} = 20^{\circ}C$
Packaging	Packaging Machine	< 1 min	$T_{ambient} = 20^{\circ}C$
	Total processing time	**225 min**	

4.3.2. *Artisanal bread manufacturing*

Artisanal-based manufacturing processes are proposed for the three smallest manufacturing scales of Chapter 3, i.e. Home Manufacture (HM), Food Incubator (FI) and Distributed Manufacture (DM). *Table 4.3*. lists the equipment, conditions, and processing time for the three scales. HM and FI manufacturing methods (see *Fig.4.2*) follow an artisanal bread making process (Gisslen, 2016). The unit operations of *Fig.4.1* are replicated by individual processes that can be developed in a domestic kitchen. While both scales share the same procedure, the different number of equipment units available per manufacturing site results in different productivity for each scenario.

Here, a stand mixer first pre-mixes the dough blend and later performs the kneading by increasing the agitation speed. The batch of mix is then rested for 10 minutes to reach the desired consistency. The dough is later divided in individual dough units of a chosen weight using a kitchen scale. Each dough is subsequently hand moulded and placed into a proofing basket, which is covered with a clean humid towel and left during 24 h in the fridge for a slow proving (Homegrown, 2013). The following day, the proved loaves are moved into a floured tin and left for 30 min to reach ambient temperature and be ready for baking (Desmazery, 2008).

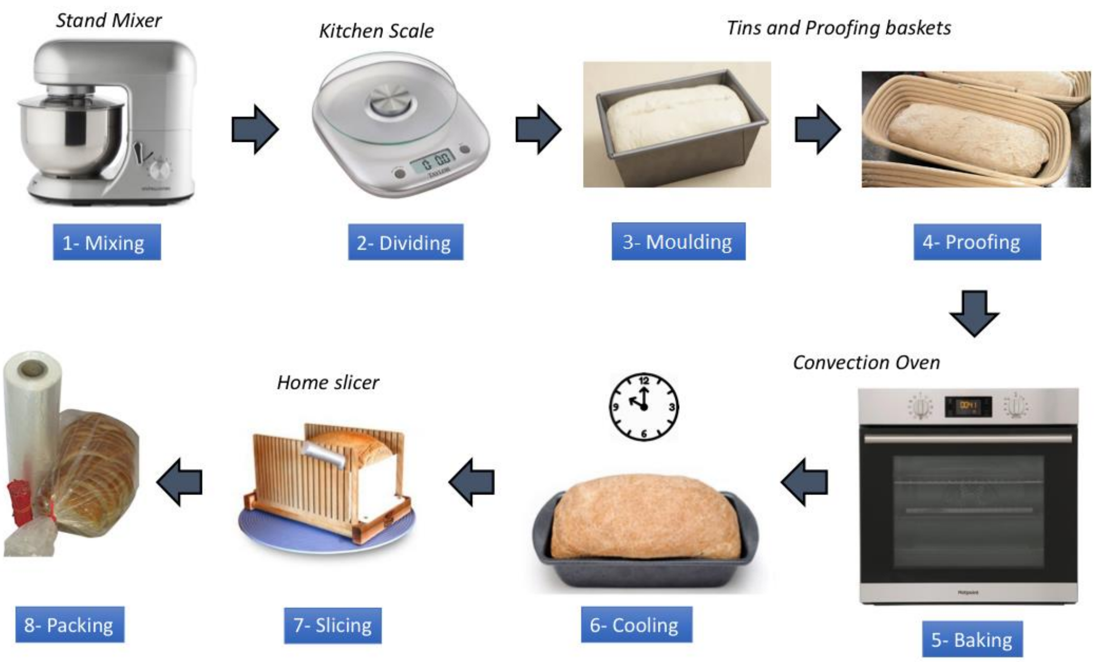


Figure. 4.2. Artisan bread manufacturing flow chart for HM and FI.

Baking takes place in a domestic convection oven. Bake time will be computed from the energy required to reach the targeted water content of the finished bread. Once completed, the bread loaves are cooled at ambient temperature. Long cooling times are not necessary as fresh bread is commonly sold still warm. Finally, the product is sliced and packaged before being sold.

A modular manufacturing approach is applied for DM. Catering size bakeries are common businesses, so modular processing lines for bread manufacturing are available in the market. *Fig.4.3* depicts the DM process.

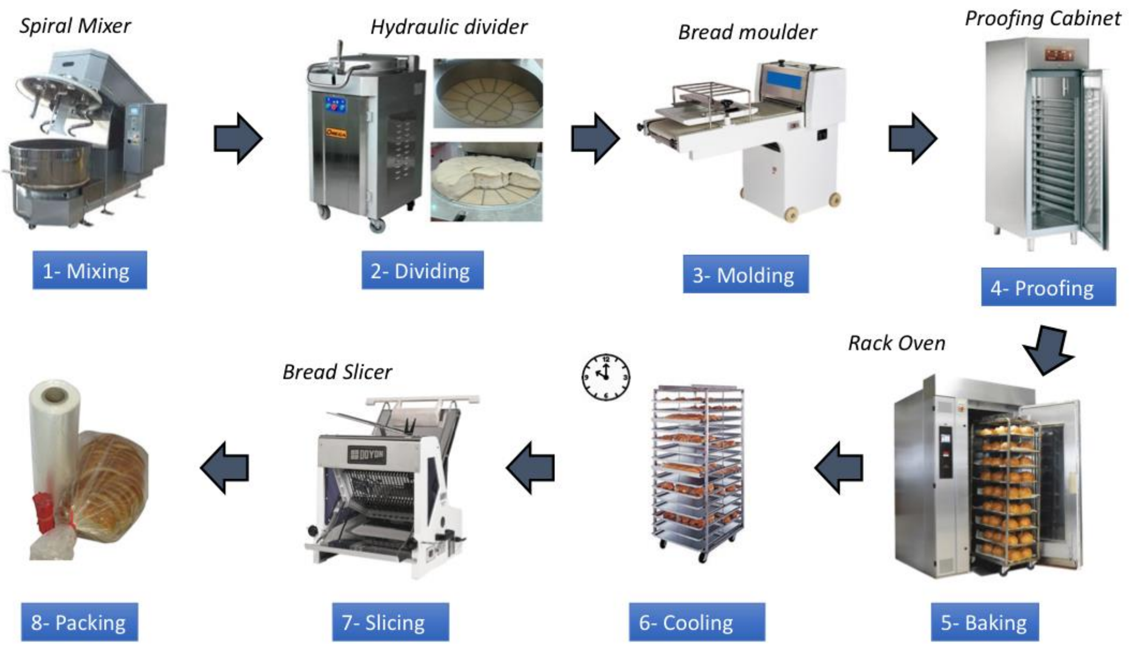


Figure. 4.3. Artisan bread manufacturing process for DM scale.

The use of specific baking equipment to perform the artisanal process makes it possible to increase productivity. Higher capacity equipment allows bigger batches for the same residence time, while a hydraulic divider and a moulding machine enable fast dividing and moulding for a higher number of loaves. Proving takes place in a proofing cabinet, where temperature and humidity are set to give industrial proofing times. The proved bread is later baked in a rack oven, which makes the transportation easier using a trolley. When the baking is completed, the batch of bread loaves is left in the room to cool down at ambient temperature. A bread slicer cuts the loaves that are next packaged manually, so the final product is ready to be sold.

Table 4.3. List of unit operations, operating conditions and equipment used for the three manufacturing scales involving an artisanal manufacturing process (batch operation).

Operation	DM	FI and HM	Main Conditions
Mixing: i) premix ii) kneading	Spiral Mixer	Stand Mixer	8 min 100 – 150 rpm 300 – 360 rpm
Resting	Mixer bowl	Mixer bowl	10 min
Dough division	Hydraulic divider	Kitchen scale	< 1 min/loaf
Dough moulding	Bread Moulder	Hand moulding	< 1 min/loaf (DM) 1 min/loaf (HM and FI)
Proofing	Proofing cabinet	Proofing basket	60 min, 32-42 ˚C (DM) 24 h, 8 ˚C (FI and HM)
Other ingredients adding	Manually	Manually	< 1 min per loaf
Baking	Rack oven	Convection oven	230-260 ˚C t_{batch} = calculated
Cooling	Natural cooling	Natural Cooling	10 min $T_{ambient} = 20^{\circ}C$
Slicing	Bread slicer	Home slicer	< 1 min per loaf
Packaging	Manually	Manually	< 1 min per loaf
Total batch time	***145 min***	**120 - 130 min (+24 h proofing)**	

4.4. Model description

Figure 4.4 shows the sequence followed to make and solve the modelling of industrial and artisanal bread manufacturing methods. The machinery involved in bread making is very specific. No design using chemical engineering methodology is performed here for any of the manufacturing scales. Commercial instrumentation, which have a maximum capacity set by the manufacturer, are considered to build each process. Mass balance sets the size and numbers of equipment per unit operation needed to reach the production rate evaluated. Energy balance computes the energy use and baking time, depending on the heating capacity of the corresponding baking equipment and batch size, for each artisanal manufacturing method. For industrial manufacturing, energy balances calculate the fuel needed in the process, as the baking time is already set following data found in literature. The estimation of the economic parameters, energy consumption and emissions associated to the manufacturing process are also implemented.

4.4.1. Model assumptions

4.4.1.1. General assumptions

- An individual sandwich bread loaf weights 800g. The average dimensions of a finished loaf are 12 cm high, 12 cm width and 34 cm long.
- The density of gas-free dough is assumed as 1270 kg m^{-3} (Campbell et al. 1993).
- Average temperatures assumed are $T_{proving}$ = 37˚C (Gally et al., 2017) for assisted proving –it excludes slow cold proving– and T_{bake} = 240 ˚C for baking (Le-bail et al., 2010; Bedrariol et al., 2019).

- The weight loss, i.e. water loss, of the dough is estimated as 14.0 % for baking (Purlis, 2011) and 1.75 % during cooling (Grenier et al., 2002). Negligible weight loss during proofing is assumed.
- In an oven operating at 240 ˚C during baking, the temperature reached by the bread crust (T_{bake}^{crust}) is assumed to be 180˚C, while baked crumb temperature (T_{bake}^{crumb}) remains lower, i.e. 97˚C (Busch, 2016).
- The ratio crumb-crust (X_{crust}) of 0.2 is considered (Le-bail et al., 2010).
- Individual factors for cost estimation, and management cost assumptions for each manufacturing scale can be found in Chapter 3 and Appendix A
- When consulting the four biggest UK supermarkets, the average market price for an 800g loaf of sandwich bread is set as 1£ –1.32$– (Tesco, 2019; Sainsburys, 2019; Asda, 2019; Morrisons, 2019).

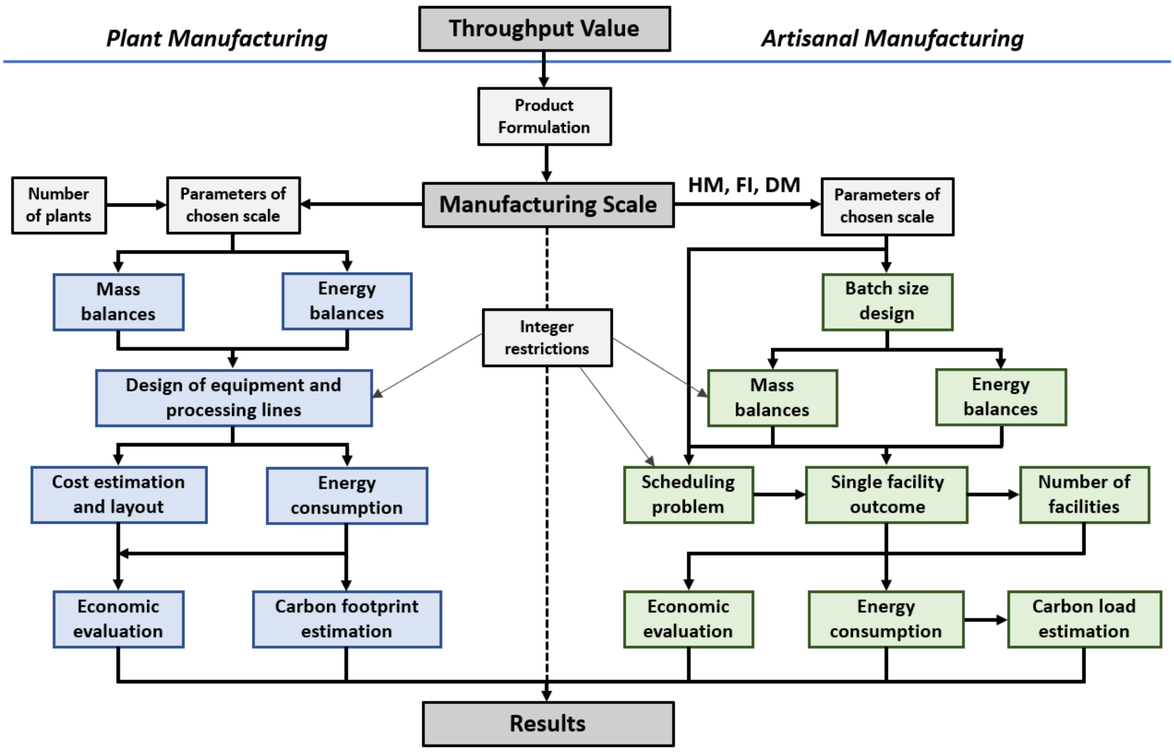


Figure 4.4. Flow diagram depicting the sequential process to build and solve the modelling of all industrial and artisanal bread manufacturing scales.

4.4.1.2. Industrial manufacturing method assumptions

- A continuous operation mode of 7 days and 3 shifts (24 h per day) is chosen for the bread plant (Maroulis and Saravacos, 2008). An annual shut down for 4 weeks to perform maintenance is assumed.
- The common mass ratio of baking tin–bread is 2:1, with one tin fitting four bread loaves (Carbon Trust, 2011).
- Steam is injected at 30 kPa in the tunnel oven during the first 2-3 min to increase bread baking quality (Stear, 1990). It is assumed 0.01 kg of steam injected per kg of bread ($X_{steam} = 0.01$).
- Steam boiler heat efficiency is taken as 72.5 % when natural gas is used as energy source, and 76.0 % if heavy oil is chosen (CIBO, 2003).
- A manufacturing plant can comprise more than one processing line. Each processing line has a maximum of one tunnel oven.

4.4.1.3. Artisan manufacturing methods assumptions

- The operation mode for HM and FI is a freelance worker scenario of 1 shift (8 h per day) for 5 days a week. DM facilities operate 7 days a week and 2 shifts (16 h).
- The batch size is set by the capacity of baking equipment for the three methods.
- For DM, cleaning is carried out by specific hired personnel during non-production hours. HM and FI workers keep 1 h of their workday to clean the facility.
- HM activity is developed in the worker's kitchen with only one piece of equipment per unit available.
- FI facility is a food incubator rented for baking. Two pieces of equipment per unit operation are assumed, so the initial batch mass will be double that of the HM facility.

- DM facility is assumed as an empty room of 20 m^2 that needs to be refurbished to develop manufacturing (cost estimation in Appendix A). One piece of equipment per rack oven for each unit operation is considered.

4.4.2. Mass balance

After the initial mixing and kneading of a batch of raw dough, sandwich bread is manufactured as individual pieces or loaves. For example, in an industrial process there is a flow of dough pieces rather than a mass flow of materials. The finished product is commonly characterised by final weight, e.g. here an average loaf weight of 800g is considered. However, the mass of a loaf changes during manufacturing stages that involve heat transfer, i.e. proving, baking and cooling. Assuming the weight loss during the fermentation of dough is insignificant, mass loss at baking (x_{loss}^{baking}) and cooling ($x_{loss}^{cooling}$) is caused by water evaporation (Zhang et al., 2017). The estimated initial mass of raw dough (${M_{loaf}}^{raw}$) corresponding to a single loaf of bread would be therefore calculated using Eq.4.1. The mass of raw material i needed for making one loaf of bread (${M_i}^{loaf}$) depends on the composition set by the recipe used. A waste factor (F_{waste}) that accounts potential material loss during processing is also considered. Ingredient index (i) runs from 1 to 7 for Eq.4.2.

$$ {M_{loaf}}^{raw} = \frac{{M_{loaf}}^{finished}}{\left(1 - x_{loss}^{cooling}\right)\left(1 - x_{loss}^{baking}\right)} \qquad \text{Eq.4.1} $$

$$ {M_i}^{loaf} = \frac{1}{(1 - \Sigma F_{waste})} {M_{loaf}}^{raw} x_i \qquad \text{Eq.4.2} $$

The production rate of bread will set the number of loaves to be manufactured in a certain time. The amount of raw materials required can be found by multiplication.

4.4.3. Energy balance

The unit operations within the process that comprise heat transfer have been identified, i.e. proofing, baking and cooling. In this section, the method used to calculate the required energy to be gained or released by a loaf of bread mass (M_{loaf}) at each step is described. Cooling is carried out naturally at ambient temperature, so the only energy consumption will be caused by the power requirements of the equipment, if any. Parameters used for these calculations, e.g. heat capacity of raw dough, are found in Appendix C (*Table C.4*).

4.4.3.1. Dough proving

Dough proving is a distinctive unit operation of breadmaking and is crucial to achieve the final structure of bread (Gao et al., 2017). During proving, the water content of the dough mix and the humidity of the environment provide the aqueous phase for yeast fermentation. Yeast metabolises flour sugars while forming carbon dioxide, that then diffuses into the air bubbles previously incorporated to the dough structure during the mixing (Córdoba, 2010). The resulting pressure rise within the gas cell nuclei causes the expansion of the dough (Zúñiga and Le-bail, 2009).

Traditional yeast proving, used for HM and FI scales, is a spontaneous fermentation (Aplevicz et al., 2014), so no energy balance is required to be performed. Conversely, in industrial and modular bread manufacturing, fermentation takes place in a controlled humidity and temperature environment to enhance yeast growth and minimise processing time. Energy requirements ($Q_{proving}^{loaf}$) involve sensible heat responsible for heating both dough ($Q_{heat-prov}^{loaf}$) and mould ($Q_{tin-prov}$). A heat loss factor for the equipment (η_{prover}^{loss}), related to loses in the combustion of a gas fired proving cabinet, is accounted as 17% of the total heat (Carbon trust, 2011).

$$Q_{proving}^{loaf} = \frac{1}{\left(1-\eta_{prover}^{loss}\right)}\left(Q_{heat-prov}^{loaf} + Q_{tin-prov}\right) \qquad \text{Eq.4.3}$$

$$Q_{heat-prov}^{loaf} = M_{loaf}^{raw}\, c_{p_{raw-dough}}\left(T_{proving} - T_{ambient}\right) \qquad \text{Eq.4.4}$$

$$Q_{tin-prov} = M_{tin} c_{p_{tin}}\left(T_{proving} - T_{ambient}\right) \qquad \text{Eq.4.5}$$

The material used for the bread tins varies depending on the assessed manufacturing scale. Industrially, the chosen material is stainless steel, while domestic bread tins are commonly made of aluminium. M_{tin} is the mass of the tin (it is assumed one unit per bread loaf), while the heat capacity of the mould ($c_{p_{tin}}$) varies depending on the material used.

4.4.3.2. Bread baking

The baking process is the most energy intensive unit operation in bread manufacturing (Paton et al., 2013). Using heat, the foam structure of the dough formed during proving is transformed into a flavourful edible product comprising a continuous porous network of interconnected gas cells (Shah et al., 1999). The most intuitive quality properties of the final product –e.g. texture, colour or taste– are strongly determined by the baking stage, including the heat applied, humidity of the baking chamber and baking time (Therdthai et al., 2002). Pyler and Gorton (2010) identify the processes happening to the dough during baking as volume expansion, crust formation, inactivation of yeast and enzymatic activities, protein coagulation and partial starch gelatinisation.

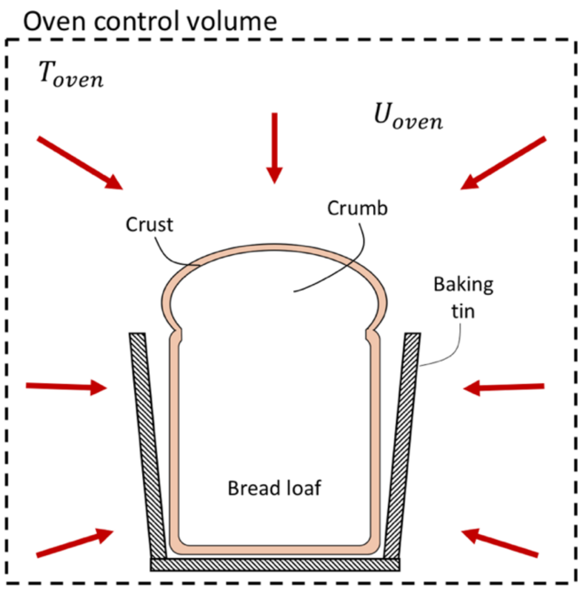


Figure 4.5. Heat transfer to the bread loaf in the oven. Crust and crumb are considered as two separated components with different thermal properties. Bread tin is also involved in the heat transfer. The baking time will depend on the temperature reached withing the oven cavity (T_{oven}) and the overall heat transfer coefficient (U_{oven}) of each respective oven used at baking.

The volume expansion of the dough is caused by the temperature rise experienced during the baking, which boosts the enzymatic activity and yeast growth previously initiated at the proving stage, and by air expansion. The inactivation of these two mechanisms takes place when temperature reaches values above 60˚C (Reed and Nagodawithana, 1990). Here, it is assumed that the mechanisms causing volume expansion and protein coagulation occur spontaneously with the increasing loaf temperature, so they do not represent any additional energy requirement.

During baking, dough changes into two different elements with distinctive appearance and properties, i.e. curst and crumb (Chhanwal et al., 2019). Crust formation happens at the surface of the loaf (*see Fig.4.5*), where the highest temperature (>120˚C) and the lowest moisture content (<0.05%) are reached. As a result, a non-enzymatic browning reaction happens, which gives the characteristic golden-brown colour of the crust (Vanin et al, 2009, Zhou and Hui, 2014). The crumb is formed from starch gelatinisation and protein coagulation of the dough (Chhanwal and Anandharamakrishnan, 2014). Crumb and crust show different heat-moisture dynamics mainly caused by a variation in the water content during baking (Vanin et al, 2009), so their thermal properties –such as the specific heat ($c_{p_{crust}}$, $c_{p_{crumb}}$)– differ. The two elements of baking bread are therefore treated as separated components in the energy balances. Starch gelatinisation, an endothermic process, takes place simultaneously during baking. The corresponding reaction enthalpy ($h_{starch-gel}$) –1.2 kJ/kg of bread dough (Le-bail et al., 2010)– is accounted in the energy balance. $Q_{heating}^{loaf}$ is the heat transferred to the loaf of bread, including sensible heat and starch gelatinisation enthalpy (see *Eq.4.6 – 4.8*).

$$Q_{heating}^{loaf} = M_{loaf}^{raw}\left(\Delta h_{crust} + \Delta h_{crumb} + h_{starch-gel}\right) \qquad \text{Eq.4.6}$$

$$\Delta h_{crust} = \frac{X_{crust}}{1 + X_{crust}} c_{p_{crust}}\left(T_{bake}^{crust} - T_{proving}\right) \qquad \text{Eq.4.7}$$

$$\Delta h_{crumb} = \frac{1}{1 + X_{crust}} c_{p_{crumb}} \left(T_{bake}^{crumb} - T_{proving}\right) \qquad \text{Eq.4.8}$$

In the mass balances, the mass loss –i.e. water loss– that bread exhibits during the crust and crumb formation at baking is computed (Zhang et al., 2017). The latent heat corresponding to that mass fraction of water ($Q_{mass\ loss}^{loaf}$) is given by *Eq.4.9*. λ_{water} is the enthalpy of vaporisation for water at standard pressure conditions. Also, energy losses caused by the heating of the bread tin ($Q_{tin-bake}$) are accounted (*Eq.4.10*).

$$Q_{mass\ loss}^{loaf} = M_{loaf}^{raw}\, x_{loss}^{baking}\, \lambda_{water} \qquad \text{Eq.4.9}$$

$$Q_{tin-bake} = M_{tin} c_{p_{tin}} \left(T_{bake} - T_{proving}\right) \qquad \text{Eq.4.10}$$

Finally, calculation of the total heating energy used for the baking of a single loaf of bread (Q_{bake}^{loaf}) follows *Eq.4.11*. The energy losses of the oven (η_{oven}^{loss}) will depend on the model used. A brief description of the baking equipment assumed for each scale depicted in this work can be found in sections 4.4.4 and 4.4.5.

$$Q_{bake}^{loaf} = \frac{1}{\left(1 - \eta_{oven}^{loss}\right)} \left(Q_{heating}^{loaf} + Q_{mass\ loss}^{loaf} + Q_{tin-bake}\right) \qquad \text{Eq.4.11}$$

4.4.3.3. Steam addition in bread manufacturing

Steam is commonly used in bread manufacturing for humidity control in proving and baking. Adding water at the baking stage creates a moistened environment that improves bread quality (Gisslen, 2016). Water condensates on the surface of the loaf and delays the crust setting, thus improving crumb texture and crust properties (Flick et al., 2015). In artisanal bread manufacturing, liquid water can be added to the oven to evaporate and create the humid atmosphere. The latent heat for steam production (*Eq.4.12*) is supplied here by the baking equipment, so it must be included in the energy balance (*Eq.4.11).* The amount of water added varies with the baking product and the type of oven, assuming here a steam/dough mass fraction (X_{steam}) of 0.01 (Gisslen, 2016).

$$Q_{steam}^{loaf} = \frac{1}{\left(1 - \eta_{oven}^{loss}\right)} \, M_{loaf}^{raw} \, X_{steam} \, \lambda_{water} \qquad \text{Eq.4.12}$$

In industrial bread manufacturing, a boiler supplies steam injected at the prover device and the first section of the tunnel oven. The energy required for steam production is therefore computed separately. It is commonly accepted that the energy used for humidity control is similar to that used for the dough heating at the prover (Carbon trust, 2011). The steam used at the proving is ca. 70% of the total steam consumption, while the 30% left is injected at the oven (Carbon trust, 2011). The mass of water (M_{steam}^{loaf}) used per loaf of bread in the industrial process is computed by:

$$M_{steam}^{loaf} = \left(\frac{1}{0.7}\right) \left[\frac{Q_{proving}^{loaf}}{M_{loaf}^{raw} \, \lambda_{water}}\right] \qquad \text{Eq.4.13}$$

The boiler duty calculation must account for the efficiency of the equipment (η_j^{boiler}), which varies with the fuel –natural gas, fuel oil or biomass (pellets)– used (see Chapter 3). The mass of fuel j (it runs from 1 to the number of alternative fuels studied) required to feed the boiler per loaf manufactured (M_j^{loaf}), is calculated considering the energy use and the lower heating value of the fuel considered (LHV_j).

$$M_j^{loaf} = \left(\frac{1}{\eta_j^{boiler}}\right)\left[\frac{\left(\frac{1}{0.7}\right) Q_{proving}^{loaf}}{LHV_j}\right] \qquad \text{Eq.4.14}$$

4.4.4. Industrial process modelling and cost estimation

As very specific equipment comprises the automated bread processing line, engineering design tools have no application here. The size of each processing unit is selected from a catalogue depending on the range of production. The number of units is constrained to integer values and will depend on the maximum capacity of each specific device and the production rate of bread loaves evaluated. The residence time is set by heuristic rules from baking industry data, as shown in *Table 4.2*.

A tunnel oven is commonly used to dehydrate the dough and achieve the desired bread consistency. The baking chamber is typically divided into different heating zones for improved control of conditions such as air velocity, temperature or water content (Corsini et al. 2015). Commercial tunnel ovens are customisable with lengths between 4.5 and 40 m (Koenig, 2019) that can reach baking capacities up to 10,000 kg/h (Khatir et al., 2015). The price of this type of equipment is commonly set as a constant price per unit length (Alibaba, 2019). A linear relation between length and capacity is assumed here, so the estimated cost of the tunnel oven can be adjusted to the bread throughput evaluated. Heating can be performed using direct-gas-fired (direct contact between flue gases and product) or indirect-fired (heat transfer achieved by convection and radiation from external heat exchangers) operation (Khatir et al., 2015; Williamson and Wilson, 2009). Direct-gas-fired ovens are more efficient as the residual energy in the combustion gases is recovered by venting into the baking chamber (Williamson and Wilson, 2009), so this unit is preferred here. The additional heat losses estimated for this equipment are insulation (4%), exhaust gas (17%) and other –e.g. cold air losses (15%) (Carbon Trust, 2011). The factor η_{oven}^{loss} in Eq.4.12 is therefore 0.36.

One industrial plant can comprise more than one processing line. Here, one tunnel oven per production line is assumed, and for throughput values higher than the maximum capacity of the oven, i.e. 10,000 kg/h, a new line, and therefore an additional oven, is considered. The other units comprising each line will be computed so they can feed the corresponding tunnel oven and process the exiting baked product. The ribbon blender operates in batch mode with a residence time enough to premix and knead the dough mass, so two units working in parallel –one discharges the blend while the other is mixing– provide a continuous flow. The size of this unit is customisable, so the price is estimated according to the capacity using the cost correlation shown in *Table A.1*. For the volumetric pressure divider, conical rounder, bread machine, spiral prover and cooling tower, their maximum processing capacity will set the number of units and therefore the expenditure required (see *Table C.3*). Finally, silos and storage tanks will have enough capacity to supply all the processing lines within the production plant for 30 days, except for the wheat flour silo that is replenished every week due to the large volume of flour required. A maximum height (15 m) is set for the silos.

Once the cost of the equipment is computed, operating cost and total capital are estimated following the individual factors method, a procedure described in Chapter 3. The same criteria used for the plant layout in cereal porridge manufacturing (Mecklenburgh, 1973) is applied here.

4.4.5. Artisan process modelling and cost estimation

Artisan-based scales operate batch processes. First, the number of loaves comprising a batch to be baked in the two type of ovens –rack oven for DM and domestic oven for FI and HM– must be computed. The available number of ovens and their capacity will determine the size of the processing batch (N_{loaves}^{batch}).

For DM, both proofing cabinet and rack oven have usually similar capacities. *Table C.2.* in Appendix C lists the chosen equipment for this scale. Based on the dimensions of a bread loaf and the volume of the oven cavity, the maximum number of trays the oven can hold and the number of loaves in a tray will set the capacity of the oven ($N_{max-loaf}^{oven}$). Reasonable separation distances between two bread tins and between tin-wall are considered. The size of the batch is also constrained as a multiple of the output achieved from the hydraulic divider that splits the dough batch in pieces. A constant number of units ($N_{loaf}^{divider}$) is always obtained from each division (here 20). The divider and the spiral mixers might be used multiple times for the batch volume set by the oven capacity.

$$N_{loaves}^{batch} = \left\lfloor \frac{N_{oven}\, N_{max-loaf}^{oven}}{N_{loaf}^{divider}} \right\rfloor N_{loaf}^{divider} \qquad \text{Eq.4.15}$$

For FI and HM, the division of the batch dough is made using a scale so there is no equipment constraining the number of pieces obtained from the division. The batch size is therefore set only by the number of loaves that the oven can hold. The batch sizes (loaves/batch) for each artisanal based method resulting from the previous assumptions are 80 for DM, 18 for FI and 9 for HM.

In section 4.4.3, the energy needed to be supplied per bread loaf in baking was calculated. The efficiency of domestic convection ovens was already evaluated in Chapter 3 –45% for a natural gas oven and 60% for an electric oven–, together with the calculation of their apparent heat transfer coefficient (h_a). The loss factor (η_{oven}^{loss}) from Eq.4.12 takes a value of 0.55 if the oven works with gas, or 0.40 if it uses electricity. Assuming that rack ovens have a similar performance to domestic oven, the baking time ($t_{baking}^{artisan}$) required for the equipment would be calculated as follows:

$$t_{baking}^{artisan} = \frac{Q_{bake}^{loaf} + Q_{steam}^{loaf}}{h_a A_{loaf}(T_{oven} - T_{crust})} \quad \text{Eq.4.16}$$

Where the energy required for a loaf of bread to be baked (Q_{bake}^{loaf}) is computed by Eq.4.12, the heat supplied to achieve a moistened environment inside the oven (Q_{steam}^{loaf}) is calculated using Eq.4.13, A_{loaf} is the loaf surface in contact with the heating environment, T_{crust} is the temperature of that surface (the crust) and T_{oven} is the temperature inside the oven. Assuming there is no interference to heat transfer when more than one loaf of bread is baked at the same time, Eq.4.16 still holds since both the required heat and the heat transfer area are proportional to the number of loaves within the oven. Results for Eq.4.16 show that 39 min are needed to bake the DM batch in the rack oven, while 41 min are needed for HM and FI scales using a convection oven.

Once baking time is estimated, the processing time for a batch of bread can be calculated. The time each batch is finished is computed. Overlap in the sequence is assumed: while one batch enters the oven, the next one starts to be processed. The time limitation is daily working hours, so the last batch before the end of the workday (deducting cleaning time) sets the maximum number of batches processed. Thus, 18 batches can be finished in a

DM facility (1440 loaves/day), 5 batches in a FI specialised kitchen (90 loaves/day) and 6 batches for a HM domestic kitchen during a day (54 loaves/day). The number of facilities needed to achieve a given global production rate can be therefore calculated.

4.4.6. Energy consumption and carbon footprint of bread making

The energy consumption and carbon emission associated with bread making for each manufacturing scale must also be assessed. Artisanal manufacturing methods comprise equipment using power to operate. Chapter 3 showed how electricity has high greenhouse gas emissions (Government of United Kingdom, 2019c). However, alternative rack (Sveba Dahlen, 2019) and domestic ovens (Samsung, 2019) using natural gas burners are also available. Although gas is less energy effective, the cereal porridge case study (Chapter 3) concluded there was a reduction in carbon footprint when using gas ovens. Both alternatives for baking will be therefore evaluated here to see the effect of the energy source on the environment impact of artisanal bread manufacturing.

For industrial bread making, electricity is used as power supply. Natural gas burners are located inside the proving chamber and the tunnel oven. The steam boiler is set to work with either fuel oil or natural gas, thus comprising a sensitivity study on the process energy use and carbon footprint estimation.

4.5. Results and discussion

The same methodology as in the previous chapter is applied here for sandwich bread manufacture. First, the model is used to simulate bread making at each scale for a wide range of throughputs. At each production rate, the model provides the production cost estimation, processing line/lines characterisation, total investment required, estimation of the facilities and manpower involved, energy demand and carbon footprint. All the manufacturing scales considered can be compared in economic and environmental terms. Also, each manufacturing method is evaluated individually. Analysis on the unit cost curves is also performed to identify the most advantageous operating regions for each scale. Finally, a scenario characterised by a production rate capable to supply a demand similar to the sandwich bread consumption in the UK is presented as a case study.

4.5.1. Operating cost evolution with throughput for bread making processes

The production costs associated to artisanal and industrial bread making methods are compared here. The objective is to study the change in production cost within a productivity spectrum, so the production rate at which each manufacturing scale becomes most economically efficient can be estimated. For this purpose, throughput is set as an independent variable that ranges from very small production rates to national bread demand values, e.g. 0.01–35,500 kg/h. The plotted throughputs along the entire Section 4.5 are defined for the industrial mode of operation (24h/day).

The modelling tool is applied along the defined production range to estimate operating cost. It is represented as the cost per kg of product manufactured, i.e. unit cost. *Fig.4.6* shows the evolution of unit cost with production rate. A different cost curve is obtained for each production method. The same uncertainty criteria (shaded area) described in Section 3.5.1.2 has been applied. Highest unit operating cost are reached at lowest productions, when the fixed costs, e.g. depreciation of instrumentation, are most important. At increasing throughputs, fixed costs spread over a higher number of units produced, while variable costs (e.g. raw materials) increase their share within the total production cost. As a result, unit cost drops. When fixed costs are negligible, unit cost reaches a plateau. The characterisation of fixed and variable cost was carried out in Section 3.5.1.1 of Chapter 3.

Artisan manufacturing methods involve lower fixed cost so they can be profitable at lower productivities. HM scale production cost quickly drops below the average market price for throughput values of 0.1 kg/h. The cheap raw materials and the low depreciation of instrumentation –the equipment for 1 facility costs 1,300 $ working during an assumed lifespan of 8 years– allow low unit cost values at small production rates. Although there is no equipment depreciation for FI method, the food incubator fee increases fixed cost and therefore productivity must be higher to achieve competitive operating costs, i.e. above 2kg/h. DM involves major labour costs that causes a loss in competitiveness for this scale. DM can only be profitable for the lowest management cost assumptions (franchise model) and the bigger facility size (comprising two ovens). When one oven per site is considered, DM cost increases ca. 14% due to the higher number of facilities required for the same bread output, which raises labour, rent and management expenses. Corporation model assumptions means that DM is unprofitable at any production rate.

Industrial manufacturing reaches the lowest cost. However, the higher fixed costs involved in building and operating a manufacturing plant require throughput values above 1,000 kg/h (SP) and 1,900 (Two plants) for the cost to drop below the bread market price. The crossover points of the cost curves linked to industrial manufacturing and artisan manufacturing methods are listed in *Table 4.4.* The estimated production rates, at which DM, FI, and HM become more economically efficient than industrial manufacture, are therefore identified including uncertainties. Results plotted in *Fig.4.6* correspond to conventional bread formulation. A variation on the cost below the 2% is found for the alternative dough recipes, so they are encompassed within the uncertainty area.

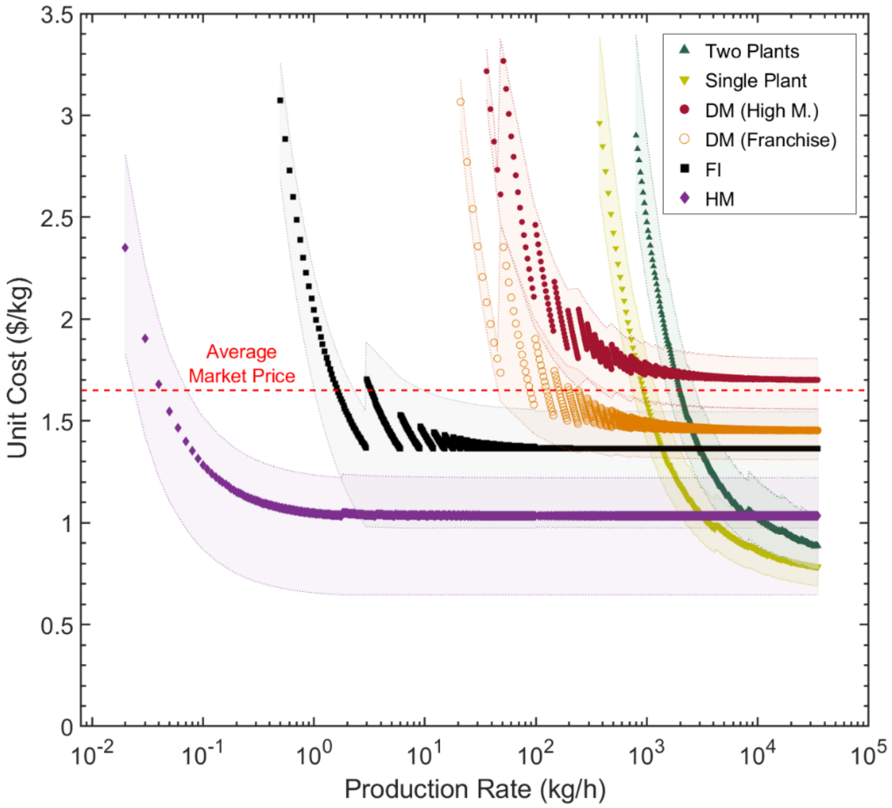


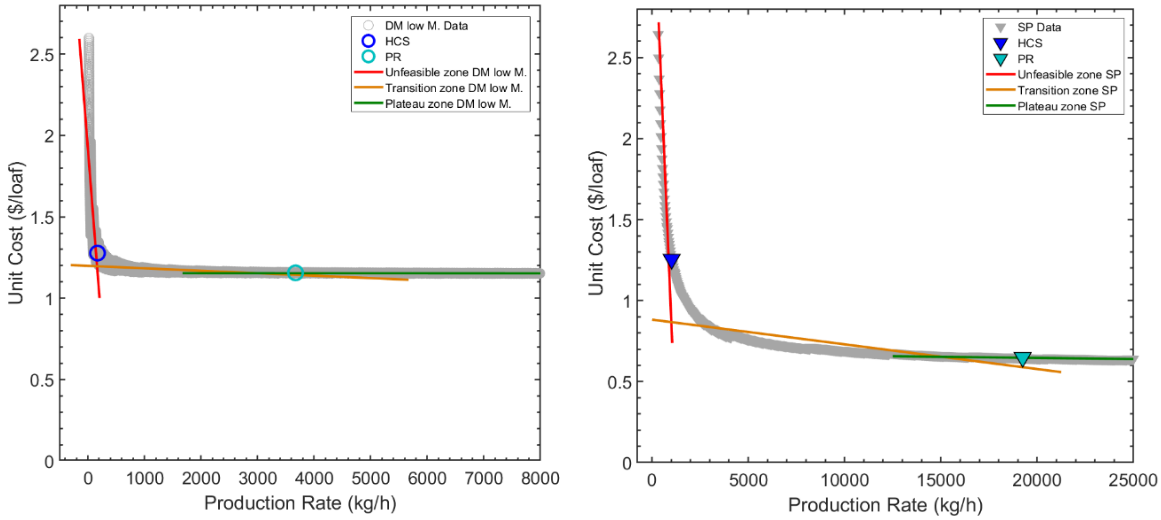
Figure 4.6. Variation of the unit cost ($/kg) for different manufacturing scales in the production of 800g sandwich bread loaves. All scales show a decreasing unit cost for increasing production rates until a plateau is reached. The shaded areas represent uncertainties at the unit cost estimation. DM data correspond to an operation using two rack ovens per facility. Logarithmic scale is set for the x-axis to see better the performance of the cost curves. The red line showing the average market price for 1 kg of sliced bread separates profitable scenarios (below) from unprofitable ones (above).

Table 4.4. Crossover points of SP and MP and the artisan bread manufacturing methods cost curves obtained from *Figure 4.6.* 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 (unitary cost – $/kg).

Throughput (kg/h) Unitary Cost ($/kg)	SP (lb)	**Single Plant**	SP (hb)	MP (lb)	**Multi-Plant (Two Plants)**	MP (hb)
HM (lb)	> 40,000 0.54	-	No crossing	No crossing	-	No crossing
Home Manufacturing	-	**3,155 1.04**	-	-	**7,950 1.04**	-
HM (hb)	1,320 1.22	-	2,755 1.22	2,850 1.22	-	9,540 1.22
FI (lb)	2,420 0.97	-	12,200 0.97	5,800 0.97	-	> 40,000 0.97
Food Incubator	-	**1,375 1.36**	-	-	**3,005 1.36**	-
FI (hb)	840 1.55	-	1,390 1.55	1,725 1.55	-	3,270 1.55
DM low M. (lb)	1,152 1.32	-	2,160 1.31	2,400 1.31	-	5760 1.31
Distributed Manufacturing (low Manag.)	-	**1,131 1.48**	-	-	**2,574 1.46**	-
DM low M. (hb)	768 1.62	-	1,296 1.59	1,680 1.58	-	3,024 1.57
DM high M. (lb)	768 1.61	-	1,344 1.58	1,680 1.57	-	3,072 1.57
Distributed Manufacturing (high Manag.)	-	**837 1.77**	-	-	**1,845 1.73**	-
DM high M. (hb)	576 1.93	-	960 1.89	1,248 1.87	-	2,208 1.84
SP (lb)	-	-	-	> 40,000 < 0.69	-	No crossing
Single Plant	-	-	-	-	**> 40,000 < 0.78**	-
SP (hb)	-	-	-	2,825 1.22	-	No crossing

4.5.2. Identification of the operational regions for the different bread making methods

The unit cost data generated by the sandwich bread modelling tool is analysed. High change in slope (HCS) and plateau reaching (PR) points are obtained, and the three regions of operation – i.e. unfeasible, transition and plateau– are identified. *Fig.4.7* shows the cost per loaf of bread for DM (franchise) and SP scales, together with the HCS and PR points and the three operational regions identified. Similar plots for the rest of manufacturing methods can be found in Appendix C (*Fig.C.1*). In addition, *Table 4.5* lists the key points, characterised by the coupled coordinates throughput/unit cost, and the linear fitting of each operating region for all the production scales.



(a) (b)

Figure 4.7. Identification of the three different operation regions defined in this work for bread manufacturing carried out in (a) DM –franchise or low management model– and (b) SP manufacturing.

Fig.4.7(a) shows that a DM scenario, organised using the franchise model, producing less than 171.5 kg/h of sandwich bread (HCS point) is operating in the unfeasible region (red line). The steep negative slope indicates that slightly higher capacities can achieve great cost reduction, so operating in that region is not advisable. The transition zone (orange line) is reached for throughputs between HCS and PR points. Within this region, a substantially capital injection is required to achieve a small improve in cost efficiency. A single DM site produces a maximum of 72.0 kg $h^{-1}facility^{-1}$. However, it works for 16 h/day while the throughput values in x-axis are defined on an industrial time basis (24 h/day), so the equivalent productivity is reduced to 48.0 kg $h^{-1}facility^{-1}$. At least four facilities are therefore needed to achieve productivities above the HCS. A plateau in the cost is reached at 3,672 kg/h, with at least 77 bakeries supplying sandwich bread. Any operation in the plateau region has reached the maximum cost effectiveness. Profits will only improve by increasing sales revenue.When high management cost is considered for the organisation of DM, higher productivities are required for a feasible operation. Transition region begins at 237.6 kg/h with five facilities working at their full capacity, while the maximum cost effectiveness can be reached by a net of 177 bakeries –more than the double than franchise management– manufacturing 8,472 kg/h of bread.

A HM facility has an actual production of 5.4 kg/h, but it results in 1.8 kg/h when the industrial time basis is assumed. The unfeasible region for a HM scale ends at 0.13 kg/h, a production rate easily achieved by a single kitchen, while six kitchens are needed to reach the plateau. For FI, working in a food incubator increases productivity (9.0 kg $h^{-1}facility^{-1}$ or 3.0 kg $h^{-1}facility^{-1}$ daily) but also unit cost. A single facility can reach the transition region and have a feasible operation, but the maximum economic efficiency involves at least 22 food incubators producing more than 64.6 kg/h.

Table 4.5. Linear fitting for all the operational region –unfeasible, transition and plateau– in which each bread manufacturing scales can perform. The high change in slope (HCS) and plateau reaching points (PR) that separate the characteristic regions are identified by an x-axis coordinate (throughput – kg/h) and a y-axis coordinate (unitary cost – $/kg), as shown below.

	Unfeasible section		HCS	Transition section		PR	Plateau section	
	slope	intercept	(kg/h) ($/loaf)	slope	intercept	(kg/h) ($/loaf)	slope	intercept
HM	-6.43	1.68	0.13 0.98	-2.62 e-03	0.83	9.2 0.83	-5.75 e-06	0.83
FI	-0.80	2.57	1.8 1.27	-0.001	1.15	64.6 1.10	-3.07 e-06	1.09
DM (Low M.)	-0.0045	1.92	171.5 1.28	-1.51 e-05	1.20	3672 1.16	-1.10 e-07	1.15
DM (High M.)	-0.0044	2.39	237.6 1.45	-7.03 e-06	1.37	8472 1.32	-1.25 e-07	1.33
SP	-0.0028	3.70	1025.0 1.26	-1.53 e-05	0.88	19250 0.65	-1.37 e-06	0.67
2P	-0.0016	3.86	1850.0 1.37	-1.19 e-05	0.99	28480 0.72	-1.39 e-06	0.75

Finally, industrial manufacturing scenarios comprising one and two plants are evaluated. The HCP point (1,025.0 kg/h) sets the lowest capacity that a single factory must reach to operate with a sensible cost efficiency. A large plant comprising five production lines can reach the plateau region –starting at 19,250 kg/h– and therefore the maximum cost efficiency that economy of scale provides (see *Fig.4.7(b)*). For two plants, HCS and PR are found at higher production rates, i.e. 1,850 kg/h and 28,480 kg/h respectively, each plant comprising four production lines to reach the plateau.

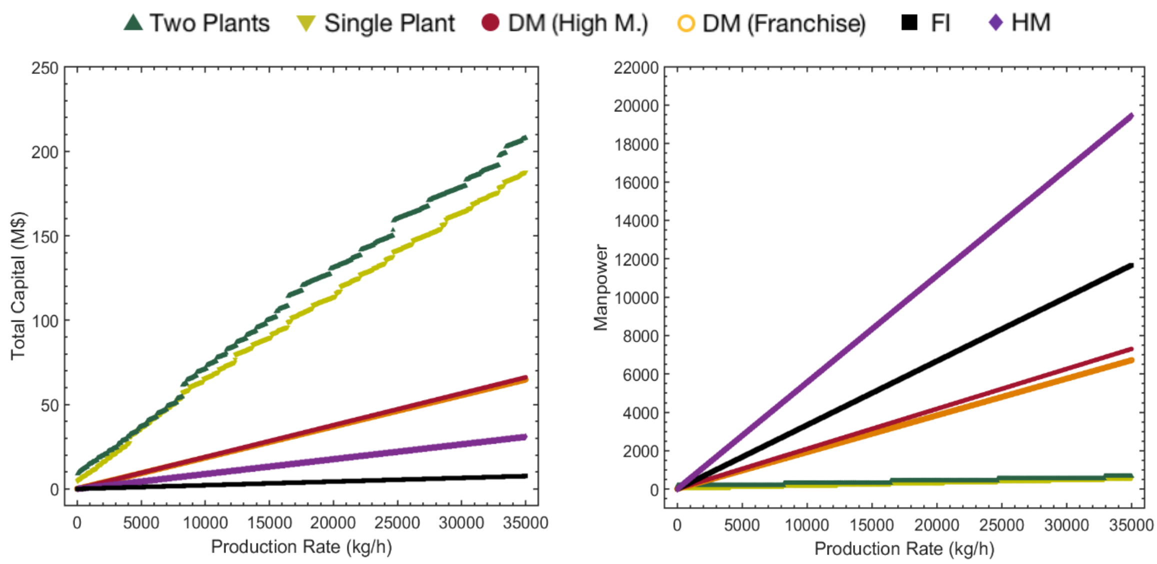
4.5.3. Total capital and manpower needs in bread manufacture.

Total capital investment includes all the funds necessary to get the project underway. This parameter can represent the barriers to start-up a new business, so it is used here to compare all the manufacturing methods.

Total capital increases with throughput (see *Fig.4.8a*). Industrial manufacturing demands the highest capital and shows the steepest growth. Steps appear when the maximum capacity of an instrument is reached so an additional unit is required, e.g. an entire processing line is added when the capacity of the existing tunnel oven is exceeded. Initially, splitting the production in two plants does not involve much higher investment, even almost overlapping when SP comprises a second processing line while the two parallel plants (with one line each) still do not reach their maximum capacity. The difference in capital however is wider at high production rates. For example, 14% more capital is needed for a bread manufacturing in 2P when compared to a SP processing.

Artisan methods require less capital investment and show a linear growth with throughput. FI has the lowest initial investment, as the model is based on freelance workers that rent building and instrumentation. Only working capital, i.e. inventory cost, is needed to start production. HM assumes that kitchenware, already owned by the worker, is used. No initial outlay for equipment purchase is required. However, the value of the assets is included in the total capital as they are the property of the worker, so any fault, breakdown or item replacement is their responsibility. Total capital for HM scales results around 13-16% of SP, having greater values at higher production rates.

DM is the artisanal method that involve the higher initial investment. Results show that capital cost for DM doubles the value of the HM assets at similar production rates. The purchase of equipment with catering-scale capacities, more than 40% of the total capital for DM, together with the higher inventory cost and sites rental deposit, are the main reason for the rise of capital cost. Still, these values are significantly lower than that required for industrial manufacturing, i.e. ranging between 28 - 35% of the SP investment.



(a) (b)

Figure 4.8. Total Capital (a) and Manpower (b) results for the four manufacturing scales in bread making.

Following the descriptions set in Chapter 3 for the manpower estimation, SP results in the lowest labour among all scales. 96 workers are needed to operate a single plant with one production line for bread making that comprises six groups of operation (Tsarouhas, 2009) and 3 shifts (5 in total including weekends). When an extra line is incorporated, direct labour –i.e. process technicians and basic workers– is required to operate adding 60 workers. Two plant manufacturing method almost doubles the total personnel of SP, as the two plants are assumed to share the senior management board.

The manpower needed for artisanal manufacturing scenarios, which is inversely proportional to the facility size, is substantially greater. *Fig.4.8b* shows that HM and FI, two self-employed models, are the scenarios involving the higher number of workers. The use of specialised bakery equipment of higher capacity in DM enables to increase the production per worker. When high management cost is assumed, extra personnel comprise the manufacturing net increasing the total manpower of DM scale.

4.5.4. Case study: UK sandwich bread demand scenario

Sandwich bread is one of the most demanded foods included in the shopping list of consumers in the UK. It is estimated that 190,000 tonnes of sliced bread loaves are annually sold (Butler, 2017a). A production rate of 23,700 kg/h can meet this demand, when the industrial operation time is assumed.

The modelling platform has been used to evaluate how each manufacturing method would perform in a UK-based framework. HM, FI, DM –with different management cost and facility size variants–, SP and MP (up to four manufacturing plants, are evaluated. The results obtained from the platform are used to compare the methods in terms of economic feasibility, energy effectiveness and environmental impact. *Table 4.6* lists those parameters considered useful for the comparison of the manufacturing scales.

4.5.4.1. Production cost

Industrial manufacturing is the cheapest method. The economy of scale makes SP reach the lowest cost per loaf, i.e. 0.64 \$/loaf (0.80\$/kg). When manufacturing is split into multiple processing plants, production cost increases mainly caused by the higher labour and management costs –e.g. unit cost rises in 0.09 \$/loaf (14% higher). *Fig.4.9* shows the evolution of cost with the number of plants. Up to 6 plants represent a profitable scenario with production cost, including uncertainties, below the average market price for a loaf of sliced bread. The trust region for the cost estimation becomes wider as a greater number of plants involve higher investment, which also has an impact in operating cost, and larger management cost.

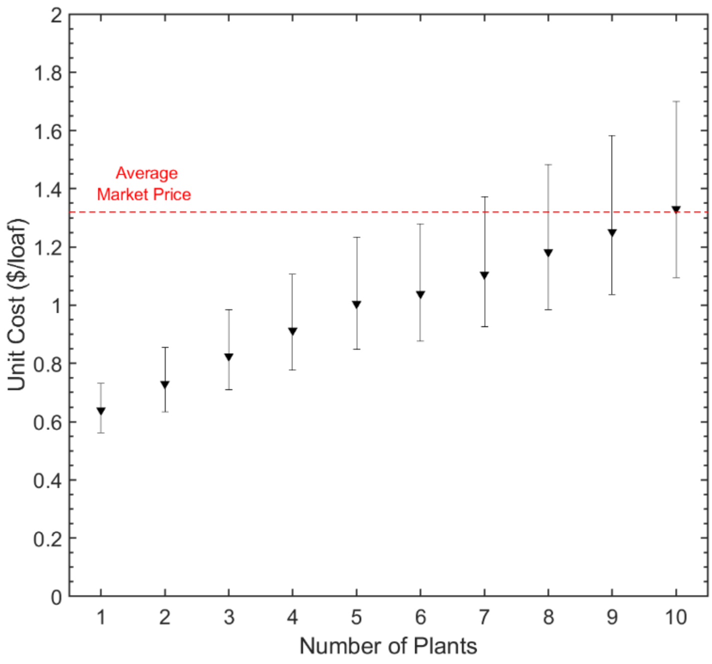


Figure 4.9. Variation of the unit cost (\$/loaf) for industrial manufacturing organised in multiple processing plants. The error bars represent the trust region on the cost estimation.

The economic competitiveness of artisan manufacturing scenarios is negatively affected by the need to purchase raw materials at retail prices, which increase raw material expenses (ca. 30%). Potential discounts, e.g. cooperative purchasing (Li, 2019), could achieve lower costs. HM is the cheapest artisan method with an estimated production cost of 0.83 kg/loaf –similar to a MP scenario comprising three plants– when a gas oven is used. This value increases by 3% if electric ovens are assumed. For FI, the rent of the food incubator is added to the production cost that rises to 1.09 kg/loaf. Although these two methods comprise a freelance scenario with no labour cost, the higher management cost resulting from the 'gig-economy' model raises their operating cost above the SP one.

DM manufacturing scales includes two possible facility sizes, i.e. including one and two rack ovens, and two alternative management levels, i.e. franchise and corporation model (as described in Chapter 3). Management cost in both models is lower than the 'gig economy' scenarios. However, the impact of labour cost depletes DM competitiveness. Bigger size DM facilities, i.e. assuming two rack oven per production line, result in 1.14 $/loaf for franchise management and 1.36 $/loaf for high management assumptions. More facilities, and hence more labour, is needed for smaller sites, so DM cost increases to non-profitable scenarios.

4.5.4.2. Total Capital

FI is the method comprising the lowest capital and, therefore, it has the lowest investment barriers to enter the market. A net of 5,600 food incubators could supply the entire UK sliced bread demand with a total capital injection of 5.1 M$, the inventory cost required to start-up the business. For HM, the resulting capital outlay (20.9 M$) does not represent the initial investment (3.9 M$), but also includes the value of the assets that might need replacement over their life span. 13,167 HM facilities would be needed to achieve the throughput demanded. DM requires total capital between 45.3 and 43.7 M$ to initiate the business. For industrial manufacturing, SP initial investment triples the DM values (132.7 M$) as more costs are needed for the building and start-up of an industrial plant. The total capital increases with the number of process plants as shown in *Table 4.6*.

4.5.4.3. Net profit

To compare the profitability of the different manufacturing scenarios, the selling price is assumed to be identical. *Table 4.6* lists the annual net income, i.e. after tax deduction, that a single facility from each manufacturing scale would get from a year of operation. Eq.3.5 is therefore applied here considering that bread is a zero-rate product in the UK (Government of United Kingdom, 2017a). A single freelance worker following the HM method would generate 7,150 $/year from the bread making activity. The fact that bread is a low value-added product, together with the small production per facility achieved when a domestic oven is used, results in a low income that might not be considered reasonable. The higher production per facility in FI cannot balance the increase in production cost caused by the food incubator's fee, which impacts on the total cost for bread making (24%). The net profit per facility falls to 5,600 $/year. For DM, franchise management is imperative to achieve profitability. A single production site with one oven generates 13,500 $/year, while a bigger site comprising two ovens increases profits to 71,250 $/year. Potential losses are expected when the corporation model is chosen for any facility size. Industrial manufacturing represents the highest profit per facility resulting in 130 M$/year for SP, while for an industrial bread making structure of two plants each factory would generate 56.4 M$/year.

Table 4.6. Economy estimation, energy demand and carbon load results for bread making in a demand scenario similar to UK sandwich bread national demand.

		Unit Cost ($/loaf)	Investment (M$)	Number of Facilities	Net Profit ($/Facility)	Total Workers	Energy consumption (kJ/kg)		Carbon load (kg CO_2e/kg)	
							Electric Oven	*Gas Oven*	*Electric Oven*	*Gas Oven*
HM		0.83	20.9	13,167	7,150	13,167	1,791	2,344	0.205	0.141
FI		1.09	5.1	7,900	5,600	7,900	1,800	2,354	0.206	0.142
DM	*low M., 1 oven*	1.26	44.4	889	13,500	5,425	1,946	2,579	0.223	0.150
	high M., 1 oven	1.52	45.3		-30,750	5,784				
DM	*low M., 2 ovens*	1.14	43.7	494	71,250	4,498	1,948	2,581	0.223	0.149
	high M., 2 ovens	1.36	44.5		-4,850	4,701				
(Industrial manufacturing scales)					(M$/Facility)		*Fuel boiler*	*Gas Boiler*	*Fuel boiler*	*Gas Boiler*
Single Plant		0.64	132.7	1	130.1	397	1,752	1,761	0.116	0.113
Two Plants		0.73	147.3	2	56.4	428	1,754	1,763	0.117	0.113
Three Plants		0.83	160.0	3	31.6	459	1,756	1,765	0.117	0.113
Four Plants		0.92	166.4	4	19.4	610	1,794	1,803	0.121	0.118

4.5.4.4. Energy use and carbon footprint

Artisan bread making methods do not represent any advantage in energy efficiency and carbon emissions at the manufacturing stage. According to the results shown in *Table 4.6*, HM is the most energy efficient artisan scale using 1,791 kJ/kg of bread manufactured when electric ovens are considered. The carbon emissions associated are estimated as 0.205 kg CO_2e/kg. When baking is performed in gas ovens, the energy consumption reaches 2,344 kJ/kg due to the lower efficiency of the equipment. However, the carbon footprint is reduced around 30% when a cleaner energy source is used, resulting in 0.141 kg CO_2e/kg. This data confirms the high energy share that baking has in the entire process. FI energy consumption and carbon footprint results are very close to HM, with a difference below 1%, as both manufacturing equipment and processing are similar. For DM, the energy demand shows a rise of 9% with respect to HM values. Carbon footprint results grow in the same proportion when electric ovens are considered for both scales. However, the difference is smaller (5%) when natural gas is assumed. In DM, bread proofing consumes natural gas, so the electricity share for the whole process is lower when compared to the smallest artisan scales.

Industrial manufacturing is the most energy efficient method with the lowest carbon emissions associated. The reduced electricity use compared to artisan manufacture (even with a gas oven) leads to the least environmental impact. SP uses 1,761 kJ per kg of bread manufactured when a natural gas boiler is chosen. 0.113 kg CO_2e/kg are the emissions estimated for that energy use. When the boiler uses fuel oil, energy efficiency improvement is negligible, but the emissions increase by 3%. For an industrial structure comprising two and three plants the numbers are very similar. Conversely, when the whole bread production is divided between four plants, energy consumption reaches values slightly above HM using electric ovens, i.e. 1,803 kJ/kg. The carbon emissions estimated are, however, a 42% lower than HM values.

4.6. Conclusion

A similar methodology to the one developed in the previous chapter has been applied for bread making, a fast-moving and semi-perishable food with short shelf life. The modelling tool scope has been extended to evaluate the effect of decentralisation in sliced bread manufacturing, in terms of economic feasibility, energy use and environmental impact. First, the evolution of the operating cost for the five manufacturing methods, i.e. HM, FI, DM, SP and MP, has been studied in a wide range of throughput values, i.e. from 0.1 to 35,000 kg/h. The results show that industrial manufacturing is the cheapest for production rates above 3,155 kg/h. For smaller throughputs, HM is the scale involving the lowest production cost. The food incubator fee has a high share of the FI total cost increasing by 31% when compared to HM values. DM has major labour costs and constitutes the most expensive artisan-based method, which requires a franchise management model (low management cost) to provide profitable manufacturing scenarios. The initial investment needed for each method has been also estimated, which shows a stepped growth with production rate. FI and HM has the lowest entry barriers as only inventory cost must be invested. DM total capital doubles the value of HM assets, while industrial processes are the scales requiring the highest investment. Labour resulted inversely proportional to the size of the manufacturing facility.

A UK demand framework –i.e. a production rate of 23,700 kg/h assuming industrial operation time basis– is evaluated as a case study. SP results the cheapest and most profitable method followed by MP comprising two plants. An industrial structure of three plants involve similar operating cost than HM, the cheapest artisan-based scale, while more than 6 plants involve production costs above the selling market price. When profitability is assessed, the low benefits produced by artisan manufacturing scenarios, e.g. 7,150 $/year per facility for HM, suggest that reductions in raw material expenditure (such as cooperative purchase) must be achieved, or the selling price should be increased over the industrial one to make feasible businesses in exchange of competitiveness. Despite DM incurring greater production costs, the higher net profit per facility (when franchise management and two ovens per site are assumed) makes this option the artisanal alternative to industrial manufacturing at the same selling price.

Finally, SP and MP (up to three plants) are the most energy efficient. The lower electricity share on industrial processing implies a lower carbon footprint for SP (25% lower than HM emissions), even when gas ovens are assumed for the artisanal bread baking. The numbers are, however, not so far away so the high impact of transportation in bread making suggest that the implementation of local bread manufacturing could result in energy and carbon emissions shavings when considering the entire supply chain.

Chapter 5

Ice cream

The following chapter is a long version of the paper published in Journal of Food Engineering, Volume 286 (Almena et al., 2020)

The modelling and simulation work, and the development of the ideas was carried out by myself along with the writing of the paper. Estefania Lopez-Quiroga reviewed the structure and provided correction to the grammar and spelling. Peter Fryer provided guidance and supervision during the research and writing/correction of the paper. The paper has been reviewed by three anonymous reviewers prior to publication.

5.1. Abstract

Decentralised food manufacture –e.g. a cloud of small local production sites and shorter distribution networks– can be a powerful tool in the development of more sustainable and safe food chains. In this context, new production scenarios based on emerging "on-demand" and "sharing" models, together with distributed manufacture methods, are potential alternatives to the current centralised paradigm. However, studies on how these new production scenarios might unfold are scarce. This work presents a techno-economic and environmental assessment of different manufacturing scenarios, i.e. Multi-Plant (MP), Single-plant (SP), Distributed Manufacturing (DM), Food Incubator (FI) and Home Manufacturing (HM) that cover a wide range of production rates (0.01 kg/h to 50,000 kg/h) and increasing decentralised production. Ice cream, with multiple formulations (i.e. premium and standard) and selling formats, is the food assessed here due to its high demand, flexibility on production methods and high energy use along the whole supply chain. Results revealed at what production level different production scales become profitable (see *Figure 5.0*), demonstrating that the shift on manufacture paradigm can be studied as a scale-down engineering problem and showing how decisions between local and centralised manufacture can be made.

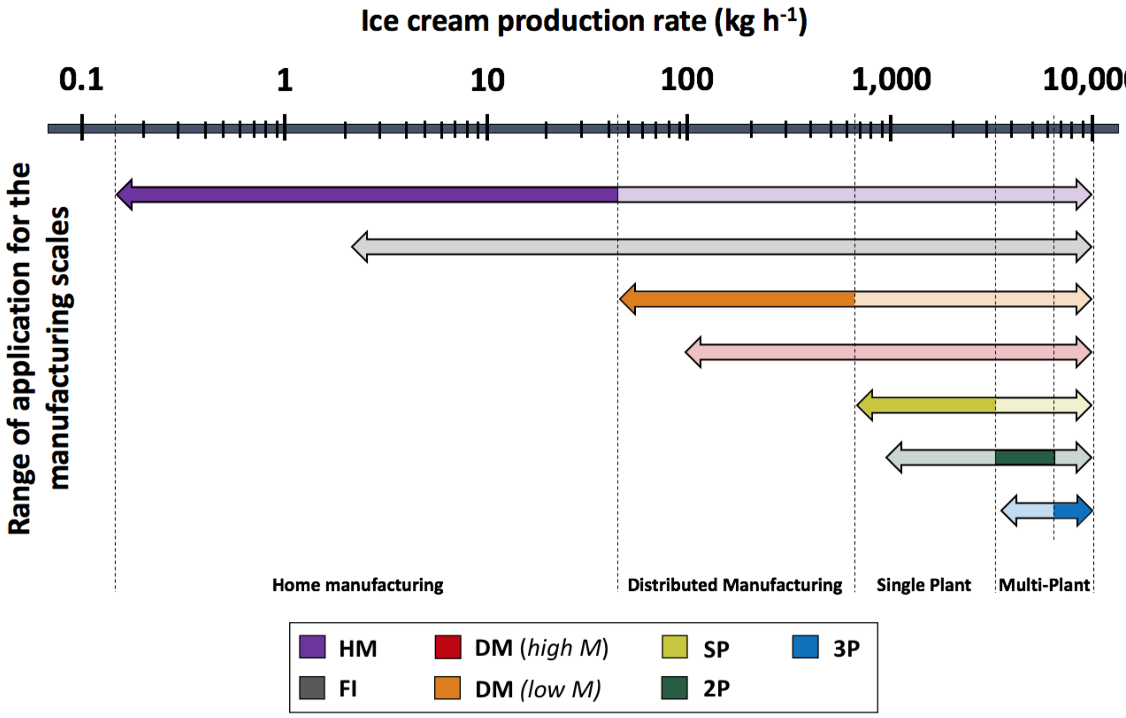


Figure 5.0. Range of applications for the different ice cream manufacturing scales, namely Home manufacturing (HM), Food incubator (FI), Distributed manufacturing (DM), Single plant (SP) and Multi-plant (MP). Arrows represent the range of application for each scale. Intense colours show the range within each scale is the preferred one to operate.

5.2. Introduction

Ice cream is one of the most popular food products, with a growth even in an economic recession scenario (DEFRA, 2019b). In the UK, an annual increase of 1.4 % in the sector's revenue has been seen since the last 5 years, with a forecasted value of 2.1 % for the next 5 years (Crundwell, 2019). Revenue values however fluctuate due to the high volatility of sales, highly dependent on weather conditions. The year-by-year warmer temperatures have doubled sales for the last two years, allowing the expansion of the sector (Butler, 2017b; Sloan, 2018). Rising exports and the increasing in take-home consumption, acknowledged in the UK, support the healthy growth and stabilise the sector's demand.

The current UK ice cream market is mostly dominated by 2 competing companies, i.e. Froneri and Unilever, that account for 85.5% of the industry revenue 2018. However, the existing saturation leads competitive manufacturers to aim for product innovation and differentiation as marketing strategies (Crundwell, 2019). Niche market opportunities are therefore created, e.g. premium and organic product demand. This, together with the medium to low barriers to enter the ice cream market, i.e. small capital investment is required due to the availability and moderate price of small-scale processing equipment for this product, a promising business scenario is established for small companies and start-ups.

Low volume and local production are common in ice cream. Local parlours can be family businesses with a long tradition (Telegraph Travel, 2018), where artisan ice cream is produced in an estimated rate between 10-30 kg/h (Williams, 2012). Ice cream vans, assuming they craft their own ice cream pre-mix –which in most cases it is not certain as the mix is commonly manufactured in high volume at an industrial plant–, are exemplars of micro scale production. The number of operating vans in the UK is estimated at around 2500 (Goodier, 2019), with a maximum throughput up to 600 cones an hour (5 kg/h assuming 2.5

oz scoops) (Tapper, 2019). The existence of these businesses shows the potential application and feasibility of a small manufacturing scenario for ice cream.

Sustainable manufacturing systems seek to implement processes involving lower global warming potential (GWP) and improved social impact, while keeping economic competitiveness (Akbar and Irohara, 2018). The study of an energy intensive supply chain, such as ice cream, is a useful contribution. Ice creams are semi-solid dairy products that are consumed in a frozen state (Deosarkar et al., 2016; Doyennette et al., 2019). Significant costs and energy consumptions are associated to their supply chain, with estimated values within the range of 3.5 – 4.0 kgCO_2e per kg of ice cream (Scottish Government, 2011; Ben and Jerry, 2016; Konstantas et al., 2019). For safety and quality reasons, ice cream needs to be kept below -15˚C until it reaches the consumer (Ben-Yoseph and Hartel, 1998). Konstantas et al. (2019) estimate that around 35-40% of the ice cream GWP is caused by the transportation and storage of the final product. An alternative model, that could minimise mileage and storage times, might reduce the environmental impact of this product.

In previous chapters, Distributed Manufacturing has been suggested as a way to create sustainable manufacturing systems and reduce the lengthy and rigid supply chains that govern conventional food manufacture (Cholette and Venkat, 2009; Brodt et al., 2013; Angeles-Martinez et al., 2018). Centralised manufacturing, based on the advantages of the economy of scale to minimise cost, has been the preferred manufacturing method during the last decades. However, in the current oversaturated market, a change in the marketing strategy, aiming at mass individualisation, challenges this manufacturing paradigm. Distributed Manufacturing is based on a restructuring of production into decentralised small-scale facilities, located close to consumers and involving sustainable and ethical manufacturing processes (Cottee, 2014; Rauch et al., 2017). DM is facilitated by digitalisation, that minimises logistics cost (Kagermann, 2015; Maslarić et al., 2016), the growth of ICT to narrow distances between manufacturers and consumers (Miranda et al., 2019), and new manufacturing technologies such as additive manufacturing and modular manufacturing (Freeman and McMahon, 2019). Local customisation and on demand supply are enabled to fulfil niche markets (Kumar et al., 2019). The resulting chain length is shortened decreasing energy use and emissions linked to product transportation and storage (Srai et al., 2016a). Thus, the Distributed Manufacturing scenarios developed in Chapter 3 could be used in the production of ice cream to provide solutions to this sector.

The chapter is organised as follows: Section 5.3 comprises the product formulation of the ice creams evaluated here. Section 5.4 describes the modelling of the thermophysical properties and rheology of ice cream, necessary for the design of the processes in the Section 5.5. In Section 5.6, the modelling is carried out, while the results are discussed in Section 5.7. Finally, the conclusions are given in Section 5.8.

5.3. Product formulation

There is wide heterogeneity in ice cream recipes. A great variety of flavours can be found in the market, meeting customer demands that differ geographically. Ice cream is composed of a plain ice cream mix, that is flavoured in later stages of the process.

The main components of the ice cream mix formulation are fats (milk and non-milk), milk solids-non-fat, sweeteners, emulsifiers, stabilisers and water. The common ranges of composition for commercial ice cream mix formulations are given in *Table 5.1*. Each component has a specific function for achieving the characterised structure and tastiness of this product.

Table 5.1. Content range and functions of components for plain ice cream mix formulations (Goff, 1997; Deosarkar et al., 2016)

Component	Composition range (%)	Properties
Fats (milk and non-dairy)	10-16	Add flavour richness Lubricate the mouth Improve smoothness of texture
Milk solids-non-fat (msnf)	9-12	Facilitate the overrun mechanism Contribute to the body and smoothness
Sucrose	9-12	Lower the freezing point Improve flavour and structure
Corn Syrup Solids	4-6	Improve body, texture and stability
Stabilizers/Emulsifier	0-0.5	Control the ice crystal size distribution Increase shelf life Improve texture and provide body
Water	55-64	Act as solvent for the continuous phase Allow ice crystal phase

Ice cream can be commonly classified as standard, premium and super premium. The main quality indicators are fat content, overrun and ice crystal size distribution. The former is controlled by product formulation, while the latter two are controlled by processing –i.e. freezing stage. Overrun has the highest impact in the economy of the process. Overrun is defined as the percent increase in volume resulted from the air incorporation during the dynamic freezing of the mix, i.e. the air content of the final product (VanWees and Hartel, 2018). Eq.5.1 calculates the ice cream overrun (Ov_{ic}), where $V_{mix}^{non-aerated}$ is the volume of pre-mix –no air incorporated– and $V_{ic}^{aerated}$ is the volume of the resulting final product.

$$Ov_{ic} = \frac{V_{ic}^{aerated} - V_{mix}^{non-aerated}}{V_{mix}^{non-aerated}} \times 100 \quad 5.1$$

Table 5.2. Standard ice cream mix formulation, taken from the ingredient list of Carte D'Or®.

Standard Ice cream Mix (100 g)

Components		**Ingredient**	**Mass (g)**	**Composition (%)**					**Total (%)**
				Fat	MSNF	Sugar	Protein	TS	
Fat	Dairy	-	-	-	-	-	-	-	**15.50**
	Non-dairy	Coconut oil**	15	100	-	-	-	-	
Msnf		Skimmed milk powder*	12	0.7	96.4	-	36	97	**11.57**
Sucrose		Sugar*	10	-	-	98.25	-	98.25	**9.82**
Syrup Solids		Glucose Syrup*	3	0.1	-	48.0	-	80.3	**3.93**
		Glucose-Fructose* Syrup	2	-	-	68	-	76	
Stabilizers		Guar gum**	0.2	-	-	-	-	90	**0.3**
		Carrageenan***	0.1	-	-	-	1.4	97.5	
Emulsifiers		Mono & Di-glycerides**	0.2	100	-	-	-	-	**0.2**
Flavour (if)		Cocoa Powder**	3	13.7	-	1.75	19.6	97	**-**
Water		Water	54.5	-	-	-	-	-	**58.68**

* Goff and Hartel (2013)
****** USDA (2020**)**
******* Webber et al. (2012)

A high overrun will require fewer raw materials for the same volume of final product. Following the composition ranges shown in *Table 5.1*, and using real commercial recipes, two different kinds of ice cream mixes –i.e. standard (Carte D'Or®) and super-premium (Ben & Jerry's Chunky Monkey®)– are formulated. *Table 5.2* shows the standard mix, whereas *Table 5.3* shows the super-premium mix. It must be noticed that these composition values are approximated as a result from fitting the common composition ranges for ice cream mixes (*Table 5.1*) and the ingredient list found on the product's label (Carte D'Or® and Ben & Jerry's Chunky Monkey®). There was no access to exact composition of both products as that information is kept confidential by the ice cream manufacturer. Standard ice cream overrun percentage is commonly set between 100-120%, and super-premium ice cream lowers the air content to 25-50 %. For standard ice cream, two flavours –i.e. vanilla and chocolate– are studied. Cocoa powder must be added to the raw mix formulation when chocolate ice cream is assumed (Goff and Hartel, 2013). The impact of the type of ice cream in the multi-scale production analysis will be evaluated here.

Table 5.3. Premium ice cream mix formulation, taken from the ingredient list of Ben & Jerry's Chunky Monkey®.

Premium Ice cream Mix (100 g)

Components		**Ingredient**	**Mass (g)**	**Composition (%)**					**Total (%)**
				Fat	MSNF	Sugar	Protein	TS	
Fat	Dairy	Cream*	25	35	5.69	-	2.1	40.69	**13.88**
	Non-dairy	Coconut oil**	2.2	100	-	-	-	-	
		Soybean oil**	2.2	100	-	-	-	-	
MSNF		Condensed Skim. Milk*	27.2	-	30.0	0	11.1	30	**9.58**
Sucrose		Sugar*	10	-	-	98.25	-	98.25	**9.82**
Syrup Solids		Molasses*	6	0.1	-	78.03	-	78.13	**4.69**
Stabilizers		Guar gum**	0.2	-	-	-	-	90	**0.30**
		Carrageenan***	0.1	-	-	-	1.4	97.5	
Emulsifiers		Egg yolk (dry)**	1	61.3	-	-	30.5	95.3	**1.20**
		Soya lecithin**	0.2	53.3	-	5	5	99	
Water		Water	25.9	-	-	-	-	-	**60.53**

* Goff and Hartel (2013)
****** USDA (2020**)**
******* Webber et al. (2012)

5.4. Modelling of the thermal properties and rheology of ice cream

To perform heat transfer calculations of the manufacturing process –e.g. freezing, heating, or drying–, characterisation of the thermophysical properties is necessary (Owen, 2006). Ice fraction, specific heat capacity, specific enthalpy and thermal conductivity are frequently required and show a strong dependency upon chemical composition and temperature (Fricke and Becker, 2001). Understanding the product rheology is also important in an efficient design. Both thermal and rheological properties are also commonly used as inline quality control parameters (Arellano et al., 2013a). For ice cream manufacture, the continuously changing composition, thermal conditions and fluid mechanics along the process makes mathematical modelling an underpinning part of the simulation.

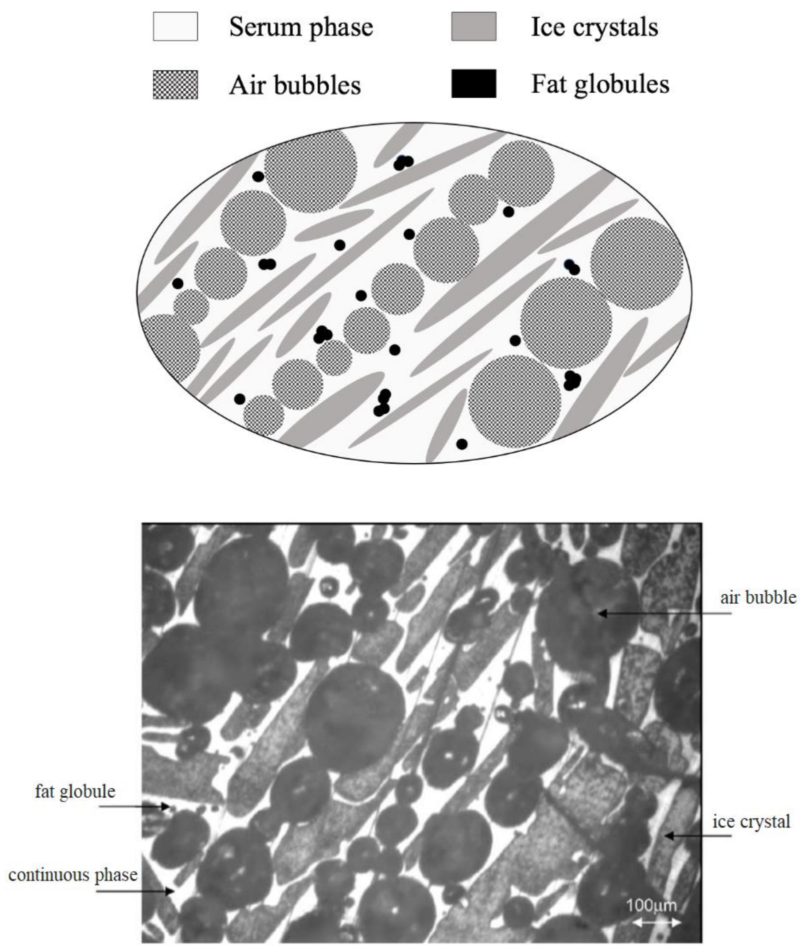


Figure 5.1. (a) Schematic representation and (b) Microscopic observation of the ice cream microstructure (Fig.7 from Cognè et al., 2013). The four phases –i.e. continuous, fat, ice and air– are recognisable by direct microscopy.

Ice cream is a partially frozen food product described as a solid foam (VanWees et al., 2019). Individual and coalesced fat globules in a partially crystalline state, ice crystals, and air cells coexist dispersed in an unfrozen serum phase that holds the structure together (Warren and Hartel, 2014). *Fig.5.1.* shows the schematic representation of the ice cream microstructure, verified by a direct microscopy observation (Cognè et al., 2013). Temperature changes, composition variation due to ingredients addition at later stages, and applying forces influence the microstructure, and hence, the product properties.

Here, the thermophysical properties are modelled. The food product is first deconstructed in its main constituents –i.e. water, protein, fat, carbohydrate, fibre and ash. Choi and Okos (1986) equations, developed to predict food component properties (see *Table D.1* in Appendix D), are used. Secondly, the viscosity of the pre-frozen mix, freezing mix and ice cream is characterized at the different stages of the manufacturing process. The model can be later used for any product formulation, and here, it is applied to standard and premium ice cream formulations developed in section 5.3.

5.4.1. Ice fraction and freezing point depression curve

Ice crystal formation during freezing has an important role in controlling the microstructure, shelf life and quality aspects –e.g. texture– of the final product (Lopez-Quiroga et al., 2016; Petzold and Aguilera, 2009; Miyawaki, 2001). Here, the freezing profile of the ice cream is calculated to compute the concentration of frozen water at any step of the manufacturing process. The aqueous phase (serum) in the mix has dissolved solutes and ions that decrease the freezing point. The freezing point depression will set the initial freezing temperature of the blend. The method described in Tharp and Young (2013), based on Leighton's work (1927), is assumed for the freezing point depression calculation (see Appendix D, section D.1). The different sugar sources, computed as sucrose equivalence, and milk salts (msnf) present in the ice cream contribute to this effect. The final equation (Eq.5.2) derived from this method is shown below. T_{IF} is the initial freezing point, k index represent the dissolved substances that are sources of soluble solids (here it runs from 1 to 8), x_k, x_{MSNF}, x_w are the weight fraction of component k, milk-solids-non-fat and water respectively and M_k, $M_{sucrose}$ are the molecular weights of component k and sucrose.

$$T_{IF} = 9.4915 \times 10^{-5} \left(\frac{\sum x_k \frac{M_{sucrose}}{M_k} \times 100}{x_w} \right)^2 + 6.1231 \times 10^{-2} \left(\frac{\sum x_k \frac{M_{sucrose}}{M_k} \times 100}{x_w} \right) + \frac{x_{MSNF} \times 2.37}{x_w} \qquad 5.2$$

The initial freezing point sets the temperature that the ice crystals start growing in the mix, and thus it is used to compute the freezing profile. The ratio of water removed as ice from the mix, i.e. the ice weight fraction (x_{ice}), is plotted against the freezing temperature (T). Cognè et al. (2013) computes the ice weight fraction using four different models: Raoult model, Miles model, Heldmann model and Chen model. The model of *Eq.5.3* (Miles et al., 1983) is assumed as it proved to give the most accurate prediction when compared to experimental data, following Cognè et al. (2013) conclusions. The dynamics of the ice crystal size distribution are not considered in this work.

$$x_{ice}(T) = x_w \left(1 - \frac{T_{IF}}{T} \right) \qquad 5.3$$

5.4.2. Specific heat

The weight additive model is chosen as the best approach to experimental data for the specific heat capacity of ice cream (Cognè et al. 2013). It assumes a contribution from each component (j) to the apparent heat capacity of the mix (see *Table D.1* in Appendix D). Latent heat of fusion of the ice (L_f) is accounted when temperature drops below T_{IF}. A correction term must be included due to the effects of freezing point depression and dilution in solution (Kumano, et al. 2007). The apparent heat capacity of the ice cream mix can be estimated following *Eq.5.4* and *Eq.5.5,* where j runs from 1 to the number of ingredients accounted:

$$c_p = \sum_j x_j c_{p_j} - L_f(T_{IF}) \frac{dx_{ice}}{dT} \qquad 5.4$$

$$L_f = 333.8 + 2.1165\, T \qquad 5.5$$

5.4.3. Density and volume fraction

The density of the mix is computed assuming ideal solution behaviour. Eq. *5.6* is used to estimate the liquid mix and the continuous phase of the frozen mix densities. The component densities (ρ_j) are shown in *Table D.1*. Once the density of the mix (ρ_{mix}) is calculated, the volume fraction of each component (ε_j) is given by *Eq.5.7*.

$$\frac{1}{\rho_{mix}(T)} = \sum_j \frac{x_j}{\rho_j(T)} \qquad 5.6$$

$$\varepsilon_j(T) = \frac{x_j\, \rho_{mix}(T)}{\rho_j(T)} \qquad 5.7$$

5.4.4. Thermal conductivity

The multiphase structure of ice cream (see *Fig.5.1*) makes thermal conductivity modelling quite complex. To simplify, fat globules are considered an additional component of the continuous (serum) phase (Cognè et al., 2013). This assumption is supported by the lower conductivity of fats –about four times– compared to the forming ice at the freezing stage. For temperatures above T_{IF}, no dispersed phase exists. The parallel model (Carson, 2006) computes thermal conductivity of the continuous phase (λ_{cont}) based on the weighted addition of the intrinsic thermal conductivity of the main food components (λ_j) (Choi and Okos, 1986; Fricke and Becker, 2001).

$$\lambda_{cont} = \sum_{j} \varepsilon_j \, \lambda_j \qquad 5.8$$

When T_{IF} is reached during freezing, the ice phase appears and grows with the temperature drop following the freezing profile. Ice crystals constitute the first dispersed phase. The De Vries model (*Eq.5.9*) is accurate for experimental data fitting, so is applied for computing the thermal conductivity of the non-aerated ice cream ($\lambda_{mix}^{non-air}$) (Renaud et al., 1992). A shape correction factor (F) is introduced to account for the nonsphericity of the crystals. The best approach to fit the experimental data assumes the dispersed ice crystals as ellipsoids with a mayor axis/minor axis ratio of 9 (Cognè et al., 2013) (see *Eq.5.10 and Eq.5.11*).

$$\lambda_{mix}^{non-air} = \lambda_{cont} \frac{1 - \varepsilon_{ice} + \varepsilon_{ice} \, F \, \dfrac{\lambda_{ice}}{\lambda_{cont}}}{1 - \varepsilon_{ice} + \varepsilon_{ice} \, F} \qquad 5.9$$

$$F = \frac{1}{3} \sum_{l=1}^{3} \left[1 + \left(\frac{\lambda_{ice}}{\lambda_{cont}} - 1 \right) f_{shape_{i}} \right]^{-1} \qquad 5.10$$

$$\sum_{l=1}^{3} f_{shape_i} = 1 \quad ; \quad f_{shape_1} = f_{shape_2} = \frac{1}{11} \;;\; f_{shape_3} = 9/11 \qquad 5.11$$

When air is added to the mix, the gas phase has to be accounted for. Assuming spherical dispersed air bubbles, a Maxwell lower bound relation (Green and Perry, 2008) incorporates the effect of the air phase to the non-aerated mix (*Eq.5.12*). The air volume fraction (ε_{air}) can be calculated from the overrun of the ice cream to be produced. Cognè et al (2013) demonstrated that this model fits experimental data accurately. Considering the thermal conductivity of air negligible compared to the one of the non-aerated mix, the ice cream thermal conductivity (λ_{ic}) calculation results:

$$\lambda_{ic} = \lambda_{mix}^{non-air} \frac{1 - \varepsilon_{air}\lambda_{mix}^{non-air}}{1 + {\varepsilon_{air}}/{2}} \qquad 5.12$$

5.4.5. Viscosity of the mix

The viscoelastic behaviour of ice cream is continuously changing during the manufacturing process. The coexistence of multiple phases and varying operation conditions –i.e. temperature, pressure or applying shear–, makes the rheology very complex.

Ice cream shows a non-Newtonian shear-thinning fluid –i.e. pseudoplastic–behaviour (Goff et al., 1994). Temperature, pressure and applying shear force, changing at each unit operation, are parameters that affect the viscosity. The Power Law model is chosen to characterise the apparent viscosity of ice cream (μ_{app}) at any stage of production (Arellano et al., 2013a; Goff and Hartel, 2013):

$$\mu_{app} = K\,\dot{\gamma}_{app}{}^{n-1} \qquad 5.13$$

Temperature affects both the consistency index (K) and the flow behaviour exponent (n) of the fluid (Elhweg et al., 2009). The relationships found by Hernández et al. (2018) and Arellano et al. (2013a) for non-aerated ice cream to calculate K (Eq. 5.14) and n respectively (Eq. 5.15), are assumed here. The shear rate ($\dot{\gamma}_{app}$) calculation method changes with the unit where the viscosity is assessed, due to the great differences in the shear stress the fluid is subjected to. The simplified Rabinowitsch–Mooney equation (Eq. 5.16) is used for ice cream flowing in pipes. The correlation of Leuliet et al. (1986) based on Fredrickson and Bird (1958) model is assumed for a scraped surface heat exchanger (Eq 5.17), and that of Calderbank and Moo-Young (1959) is used considered for a stirred tank using a Rushton turbine for agitation – $k_t = 11.4$– (Eq 5.18) (Campesi et al., 2009).

$$\begin{array}{lll} K_{mix} = 0.5838 & for & T \geq T_{IF} \\ K_{ic} = 0.5838 + 10.16(T_{IF} - T) & for & T < T_{IF} \end{array} \qquad 5.14$$

$$\begin{array}{lll} n_{mix} = 0.55 & for & T \geq T_{IF} \\ n_{ic} = n_{mix}\left[(1-\alpha) + \alpha\, exp\left(\frac{-\varepsilon_{v,ice}}{\beta}\right)\right] & for & T < T_{IF} \end{array} \qquad 5.15$$

$$\dot{\gamma}_{wall} = \left(\frac{3n_{ic}+1}{4n_{ic}}\right)\left(\frac{4\,\dot{V}}{\pi\, r_i{}^3}\right) \qquad 5.16$$

$$\dot{\gamma}_{app} = 3.213 \times 10^4 . 1.45^{N_{blades}}\, n_{ic}{}^{-0.7115}\, \dot{V}_{liquid} + 23.44\, \dot{V}_{liquid}{}^{-0.03}\, n_{ic}{}^{0.1754}\, \omega_{SSHE} \qquad 5.17$$

$$\dot{\gamma}_{app} = k_t \left(\frac{4n_{mix}}{3n_{mix}+1}\right)^{\frac{n_{mix}}{n_{mix}-1}} \omega_t \qquad 5.18$$

5.5. Different manufacturing processes design

Following the methodology of Chapter 3, different manufacturing scales, characterised by a decreasing degree of decentralisation, are designed here for ice cream production. Two different processes have been considered for multi-scale manufacture characterisation: industrial and artisanal production. The unit operations comprising ice cream manufacturing (VanWees and Hartel, 2018; Goff and Hartel, 2013; Tharp and Young, 2013) are (1) mix blending, (2) pasteurisation, (3) homogenisation, (4) Ageing, (5) Flavouring, (6) Freezing, (7) Packaging and (8) Hardening. Both industrial and artisanal processes comprise the whole set of unit operations.

5.5.1. Industrial manufacturing process

For high-volume production, ice cream is manufactured in a single industrial plant (SP) –comprising the most centralised manufacturing model– or a certain number of them (MP), showing certain decentralisation while using the same production method. *Fig.5.2* shows the flowsheet designed here that represents standard and premium ice cream process lines. *Table 5.4* lists the main operating conditions of the process, together with the selected equipment to perform the unit operations.

Table 5.4. Unit operations, operating conditions and equipment used for industrial (continuous and batch) ice cream manufacturing processes.

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

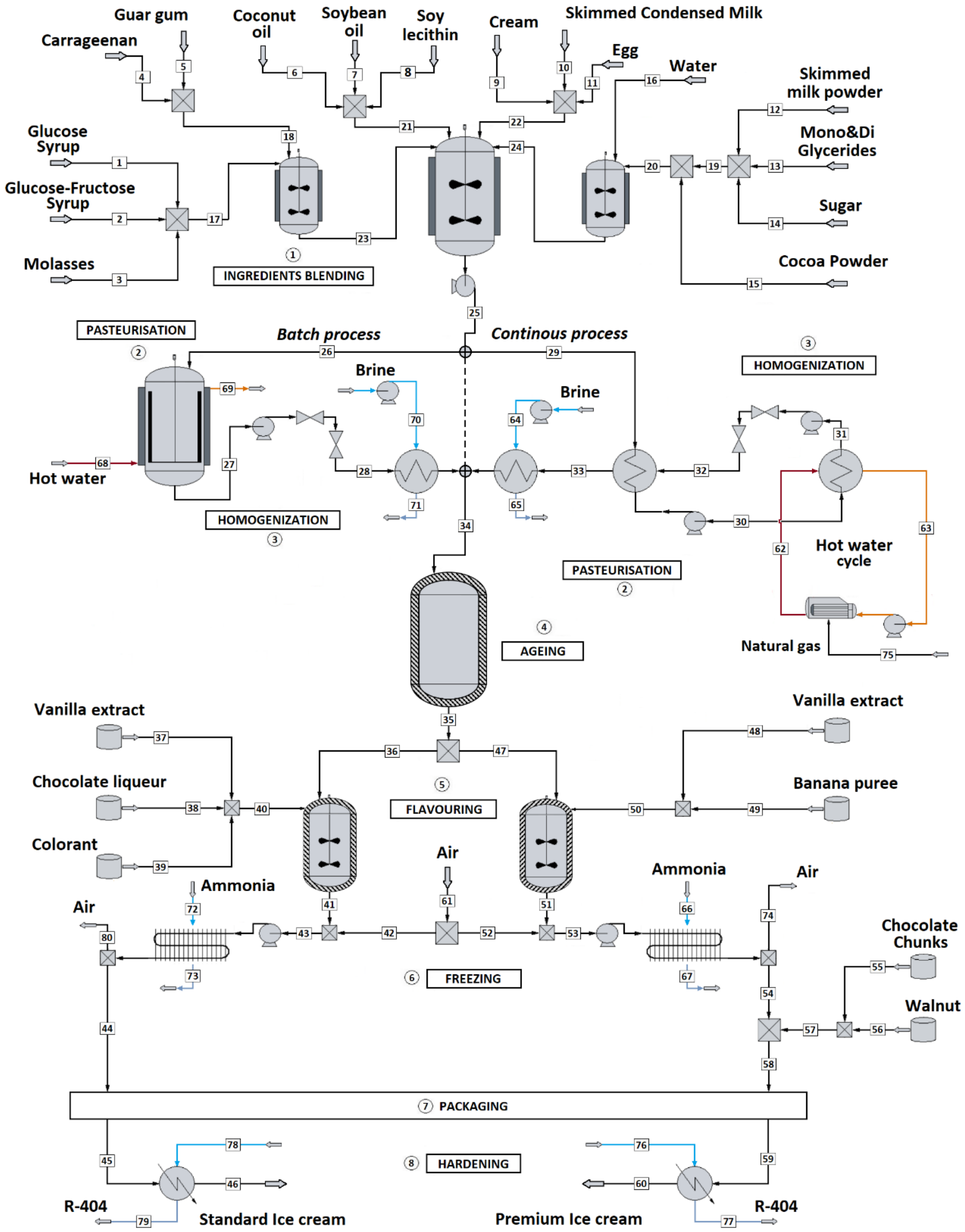


Figure 5.2. Ice cream plant production flow sheet depicting all the steps of the industrial process. Both batch and continuous pasteurisation alternatives are shown.

The plain ice cream mix is prepared in three mixing steps. First, stabilizers are dispersed in a low water activity liquid –i.e. sucrose syrups– using a high shear blender, while dry ingredients are hydrated separately in a second vessel. Both streams and the rest of the raw materials are then incorporated to a large stirring tank, where mixing takes place for 15 min (Green and Perry, 2008). When the blend is finished, the ice cream mix is pasteurised. Continuous or batch pasteurisation is performed depending of the capacity of the designed plant. Temperature and time of pasteurisation must follow the ruling national regulation at the plant location. At the pasteurisation temperature, the blend is subsequently driven into a two steps homogenisation to form the fat emulsion. Then, the pasteurised and homogenised mix is cooled down and stored for ageing to allow fat crystallisation and the full hydration of proteins and polysaccharides.

When the ageing is completed –it usually takes place overnight– the mix enters the flavouring tank for adding the flavours and colorants. The flavoured mix is then carried into a dynamic freezing stage, air is incorporated, and small dispersed air bubbles and ice crystals are produced. Chunks can be added to the semi-frozen ice cream, that is later packaged. Finally, the ice cream packages go through a hardening tunnel to decrease the core temperature below -20˚C. An efficient hardening prevents new ice crystals formation and preserves the fine ice crystals and air cells structures achieved by dynamic freezing. Thus, a high quality, stable and safe final product is produced, ready to be stored, distributed and commercialised.

5.5.2. Artisan manufacturing processes

For the smallest manufacturing scales, artisan production is proposed. Three different manufacturing scales use this method for ice cream:

i) *On-demand economy*: Home Manufacturing (HM). The most decentralised method, comprising the smallest throughput per facility, is based on domestic kitchen production. Individual freelance workers develop the activity at their own home following the ‘gig-economy’ model and sell ice cream on-demand (Gleim et al., 2019).

ii) *Sharing economy*: Food incubator (FI). Under-utilised assets, comprising specialised equipment, are rented to freelance workers for producing ice cream and supply it on demand (Alonso-Almeida et al., 2020).

iii) Distributed Manufacturing (DM). The production of ice cream is divided into scattered small catering size facilities. A combination of sole proprietorship and corporation model is assumed here. Thus, two management cost alternatives –i.e. *low management* (*franchise)* and *high management*– are considered within this method.

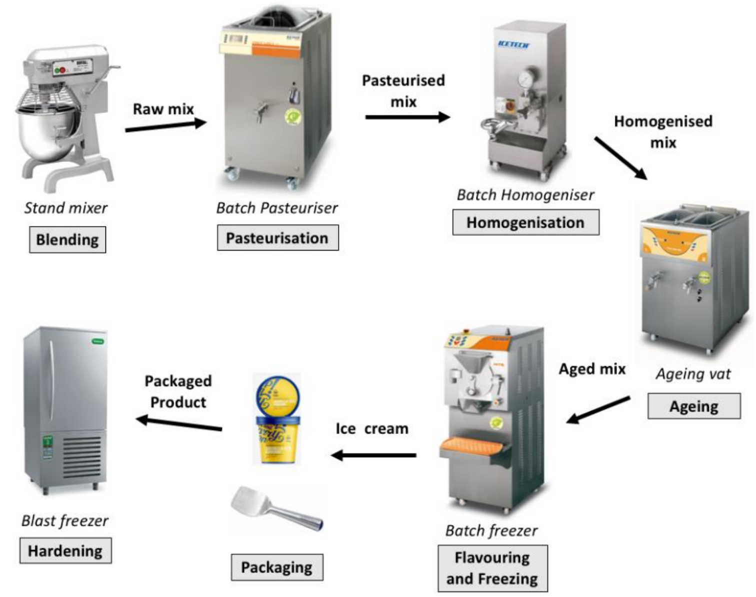
Artisan manufacturing comprises the same unit operations of industrial processing, but using equipment suitable for domestic manufacturing and batch operation. *Table 5.5* lists the equipment used for each manufacturing scale that is based on artisanal production.

A modular manufacturing approach is chosen for the DM scale (*Fig.5.3a*). Complete ice cream process lines of different sizes are available in the market (IceTech, 2019), as catering-scale ice cream production businesses are common. Depending on the production rate proposed, the platform selects the most suitable size for the process design and cost estimation. The mix is blended in a catering stand mixer and then is pasteurised using a batch pasteuriser. The safe mix is then homogenised and stored in an ageing vat to cool and rest overnight. The aged mix is then flavoured in the batch freezer stirrer, and later frozen to a semi-solid stage. Chunks are added to the extruded ice cream by the dispenser, so the product is ready to be manually packaged. Finally, the packaged product is hardened in a blast freezer, thus resulting ready to be stored.

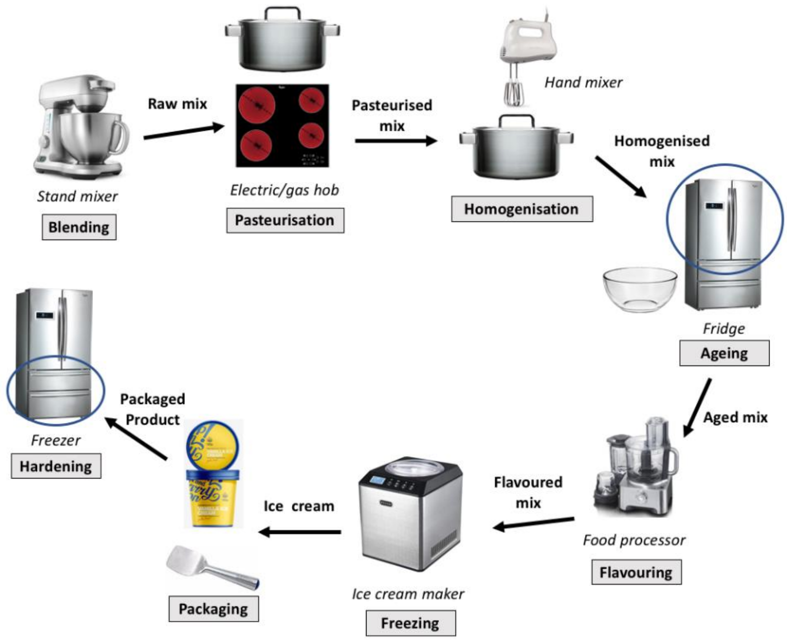
HM and FI scales follow the flowchart shown in *Fig.5.3(b)*, based on the use of common kitchenware. The stirred mix is pasteurised in a pot using an induction stove. The mix is homogenised with a high-speed hand mixer, to achieve an emulsion from all the ingredients at the pasteurisation temperature. The mix is then placed into bowls and cooled down in the fridge, where it will rest overnight at 4˚C. The aged blend is then flavoured by adding the rest of the ingredients, stirred and later frozen using an ice cream maker (HM) or a 3-in-1 ice cream machine (FI). Chunks are added here, and the product is packaged and stored in the freezer compartment, where the hardening takes place.

Table 5.5. Unit operations and equipment used for artisan (batch) ice cream manufacturing processes. The units for each parameter (unless specified in the table) are watt for power (P), cubic meter for volume (V), and dollar for price (p)

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



(a)



(b)

Figure 5.3. Artisanal manufacture flow chart for (a) Distributed Manufacturing and (b) Food Incubator and Home manufacturing. The industrial unit operations are adapted to be developed as a domestic kitchen batch process.

5.6. Model description

The basic stages accomplished during the process flowsheeting performed to solve the model are shown in *Fig.5.4.* Each individual stage is explained in the following sections.

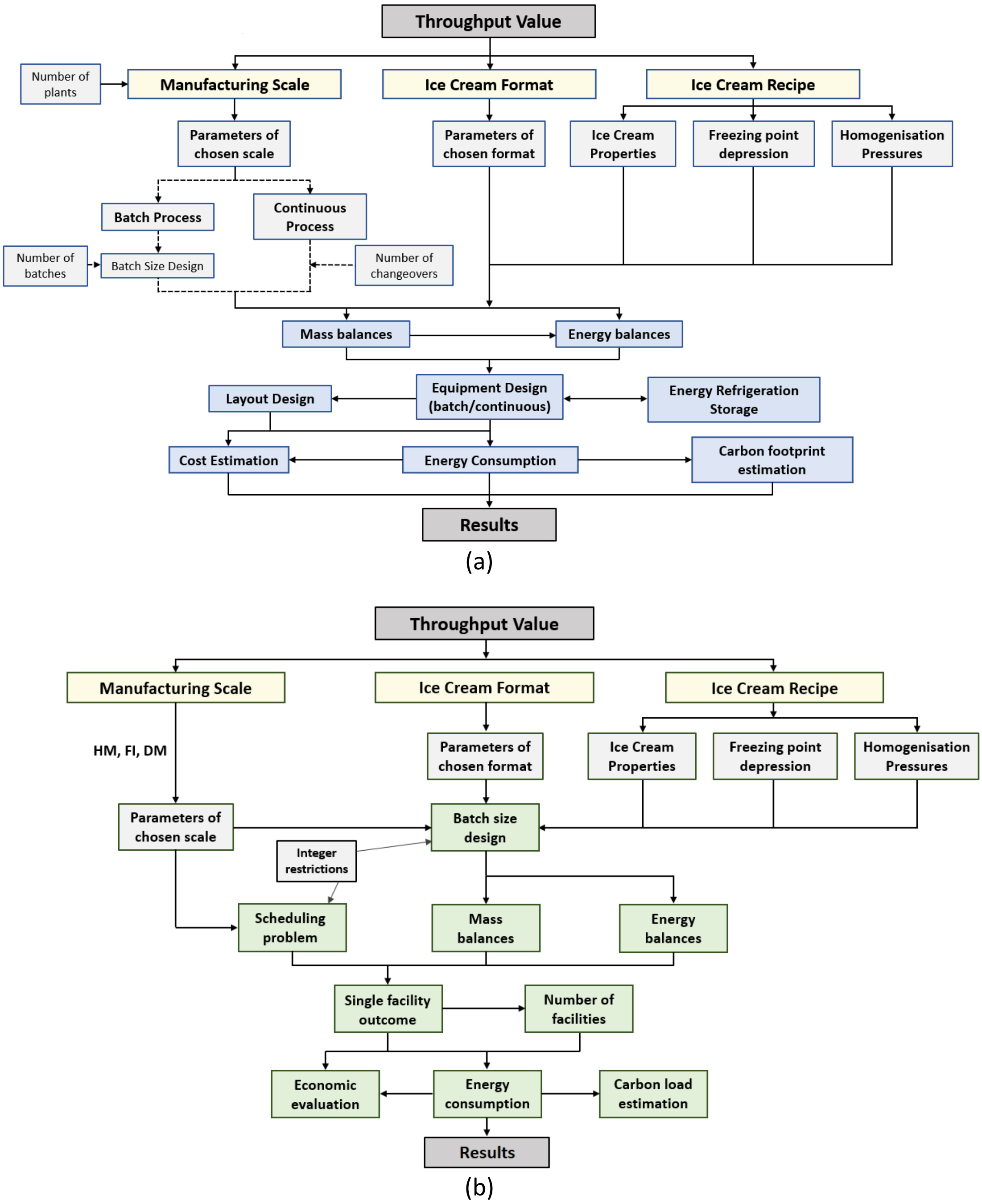


Figure 5.4. Flow diagram representing the sequential process to build and solve the modelling of (a) industrial –batch or continuous–and (b) artisanal ice cream manufacturing scales.

5.6.1. Model assumptions

5.6.1.1. General Assumptions

- Standard ice cream is sold in one litre tubs, while two formats –150 ml and 500 ml– are considered for premium ice cream. Average market prices, set by the four biggest UK supermarket, are 3.5 £/unit, 3 £/unit and 5 £/unit respectively (Tesco, 2019; Sainsburys, 2019; Asda, 2019; Morrisons, 2019).
- There are no product changeovers assumed.
- Ice cream overrun for the standard ice cream is 110% and for the premium ice cream is 27%, following the cited commercial product examples.
- The composition of the 24 ingredients accounted is listed in *Table D.2* of the Appendix.
- Homogenisation pressure at the first stage is dependent on the fat content of the mix. According to product formulation, standard ice cream should be homogenised at 1.26 MPa and premium ice cream at 1.38 MPa. The second stage is set in 3.50 MPa for both formulations (Goff and Hartel, 2013).
- A draw temperature –i.e. outlet temperature at the freezer– of -6˚C for the semi-frozen ice cream is assumed (Hartel, 1996). The ready-to-store industrial ice cream requires a -25˚C temperature, while -18˚C is assumed for the artisan product (Goff and Hartel, 2013).
- A waste factor of 0.1 % and 0.5 % per unit operation for the industrial and artisan processes is, respectively, accounted in the mass balances.
- The pre-aged mix is prepared during the workday and stored overnight. The aged mix of the previous day is processed and finished, providing the commercial product.
- Value added tax for ice cream in the UK is 20% of its market price (Government of United Kingdom, 2017a) and the Corporation tax reduction is the 19% of the Gross Profit (Government of United Kingdom, 2019b)
- Management cost estimation for each manufacturing scale can be found in Chapter 3.

5.6.1.2. Industrial production method assumptions

- An operation mode of 5 days and 2 shifts (Maroulis and Saravacos, 2008) is assumed for the ice cream plant, allowing an overnight ageing of the mix. The plant annually closes for 4 weeks to perform maintenance.
- A daily starting up time of 15 min and a cleaning time of the line of 2h are established (Kopanos et al., 2012).
- Only one production line is assumed per manufacturing plant. This is a simplification to study the effect of scale on the process line, as a centralised plant will normally have multiple lines.
- 80% of regeneration yield is assumed at the continuous pasteuriser (Goff and Hartel, 2013). Standard dimensions for PHE are shown in *Fig.5.8*. A 20% above the computed holding tube length is assumed for a safe pasteurisation.
- Heat transfer auxiliary fluids have a temperature gradient of 10˚C between the inlet and outlet of the unit (Green and Perry, 2008). Inlet temperature of hot water and brine are 90˚C and 2˚C respectively.
- The operation pressure at the freezing barrel is 0.51 MPa (Clarke, 2004). Four blades are assumed, with an oversize factor of 0.1 m over the barrel length. The useful heat transfer length is assumed to be 2/3 of the total barrel length, and the gap between the cylinder wall and the blades is 0.01 m (Boccardi et al., 2010).
- The shear rate of a flowing liquid at the wall is assumed to be 120 s^{-1}, while at the centre of the conduit it takes zero value (Goff and Davidson, 1992). In a fully baffled mixing tank, the wall shear rate is approximately half of the shear rate of the agitated fluid by the impeller (Mitsuishi and Miyari, 1973).
- The refrigeration cycles operate at saturation conditions. Ammonia expansion-compression cycle temperatures are -33.6˚C (0.14 bar) and 25˚C (10.04 bar), while for R404 a cycle temperatures of -40˚C (1.325 bar) are assumed. A Carnot simple cycle (efficiency factor of 0.6) is considered here (Sinnott and Towler, 2013).
- Stirred tanks and storage units –i.e. silos– have been oversized following the corresponding rules of thumb (Walas, 1990).

- The annual specific energy consumption for chilled stores is 44.3 kWh m^{-3}, while for frozen stores it increases to 61.9 kWh m^{-3} (Tassou et al., 2008; Evans et al., 2011).
- Working capital is assumed as the production cost of one month of ice cream, meeting the product storage time of common ice cream industrial plants (Goff and Hartel, 2013).

5.6.1.3. Artisan based production methods assumptions

- The operation mode for HM and FI is 5 days and 1 shift, as they represent a freelance worker scenario. DM replicates industrial processing, operating 5 days and 2 shifts.
- Cleaning time of 1 h is assumed within the daily working time, thus keeping food safety.
- A single artisan facility has only one processing line. HM line comprises one piece of each equipment, FI has two items of each instrument available, and DM processing line consists of a single module per unit operation.
- The specifications of each instrument –i.e. dimensions, production capacity, power consumption or price– are found in their respective catalogue (see *Table 5.5*).
- The processed product volume shall not exceed ¾ of the equipment's maximum capacity.
- Non-overlapping steps are assumed for FI and DM processes. In HM, freezing and pasteurisation overlaps due to the smaller number of actions carried out by the cook.
- The cooling capacity of the ageing vat is assumed to be similar to the batch freezer's in DM manufacturing lines. The heating capacity is estimated as the double for the batch pasteuriser.
- HM ice cream makers cannot reach the degree of overrun set for the standard ice cream. The instrument with highest overrun (53 %) in the market is assumed for the modelling of the standard ice cream production at the HM scale (See Appendix D).
- The efficiency of the heat transfer stove/vessel-load for a domestic induction hob is 95% of that set by the manufacturer (Acero et al., 2008; Villacis et al., 2015; Adhikari et al., 2016). The ice cream will be cooked at 1/3 of maximum power to avoid

damage, and then is kept at 70˚C during the pasteurisation time. Heating of the pot is accounted as an energy loss of the pasteurisation step. Radiation and convection losses are also assumed, respectively computing 16% and 6% of the heat transfer in a cooking pot (Berick, 2006).

- Working capital is equal to the production cost of an ice cream volume similar to the maximum capacity of the storage.

5.6.2. Mass and energy balances

The laws of mass and energy conservation are applied here, as Eq.5.14 states:

$$\chi_{in} + \chi_{produced} = \chi_{Accum} + \chi_{out} \qquad 5.14$$

where χ can be either mass (stream or individual components) or energy. Mass balances will allow calculation of the raw materials required for a chosen production rate and size the designed equipment. Accumulation is assumed for batch units, where materials are processed during the residence times compiled in Table 5.4 (industrial scale) and Table 5.5 (artisanal scales).

Energy balances and thermodynamics are key in the effective design of the processing equipment, and also allow to compute the energy requirements of the process. Pasteurisation, cooling, freezing and hardening are the unit operations involving energy transfer in the ice cream manufacture and are assessed in the next sections.

5.6.3. Industrial process modelling

5.6.3.1. Pasteurisation of the ice cream mix

Pasteurisation can be performed either as a batch or continuous process. Batch operation requires longer pasteurisation times at lower temperatures (LTLT), while continuous pasteurisation reaches higher temperatures in a very short time (HTST). The operating conditions for both operations are regulated by the government where the product is commercialised. In the UK, LTLT has to be carried at 69.4˚C for a minimum of 30 minutes, while HTST requires the mix to remain at 79.4˚C during at least 15 seconds (UK Statutory Instruments, 1995). Batch pasteurisation is commonly preferred for production rates below 600 l/h (Goff and Hartel, 2013), while for larger throughput, the modelling platform selects a continuous operation.

<u>*Batch Pasteurisation (LTLT)*</u>

A jacketed stirred vessel is chosen to perform LTLT pasteurisation (*Fig.5.5)*. The full design procedure is shown in Appendix D, Section D.4. Previously, the mix has been blended in the same vessel. The size of the vessel is related to the amount of plain mix needed to reach the set production. Rules of thumb (Walas, 1990) are applied to design the specifications of the vessel –i.e. diameter, length, baffles and stirring turbine– that contains the volume of blend batch (V_{batch}), given by *Eq.5.15*.

$$V_{batch} = \left(\frac{1}{N_{b-d}} \times \frac{\dot{m}_{mix} \ t_{p-d}}{\rho_{mix}{}^{raw}(T_{blending})} \right) \tag{5.15}$$

When the blending time finishes, the mix is heated up to the pasteurisation temperature. Only sensible heat is involved, and the required heat supply is calculated by *Eq.5.16*.

$$\dot{Q}_{heat} = \frac{m_{batch}}{t_{heating}} \int_{T_{blending}}^{T_{pasteur}} C_{p_{mix}} dT \qquad 5.16$$

External jacket and internal coil are the most common installations for heat transfer in a vessel, the former being the option here. Design variables are the rotational speed of the blades (ω_t) and the thickness of the jacket (δ_{jk}). The vessel-jacket heat transfer can be improved increasing the agitation speed –enhancing the convection coefficient on the mix side– and lowering the jacket thickness –higher Re and hence convection coefficient on the jacket side. If the jacket cannot supply the demanded heat for a safe pasteurisation, an internal coil is needed. A higher heat transfer surface is then available, the number of turns being the decision variable.

An algorithm has been implemented for the optimal design, i.e. the one that meet capacity, energy and mixing requirements, of the heat transfer installation within the batch pasteuriser at flexible capacities (see *Fig.5.6*). First, the thermal properties of the mix and the heating fluid, the mass balances and the energy balances are computed for a selected plant throughput. The vessel is then sized ($A_{heat-trans}$), and the theoretical overall heat transfer coefficient ($U_{theoretical}$) is obtained using the general equation for heat transfer across a surface (*Eq.D.19*) and assuming a resistance model (*Eq.D.21*). Next, the heat transfer coefficient on the mix side (h_i) is calculated using Chilton, Drew and Jebens correlation (Sinnott and Towler, 2013). A minimum rotational speed of the stirring turbine (N_t) within the set boundaries, that achieve a Re above 2,000 (turbulent regime), is found by a first iterative routine. The effect of the shear stress is also accounted in the calculations, due to the non-Newtonian behaviour of the ice cream mix (Eq.5.13 and Eq.5.18). A second iterative process is formulated for obtaining a sufficient heat transfer coefficient on the jacket side (h_0), computed using Davis equation (Davis, 1943; Ocon and Tojo, 1980), that meets the theoretical requirements of the heat transfer. The jacket thickness (δ_{jacket}) is here the constrained decision variable that controls the heat transfer.

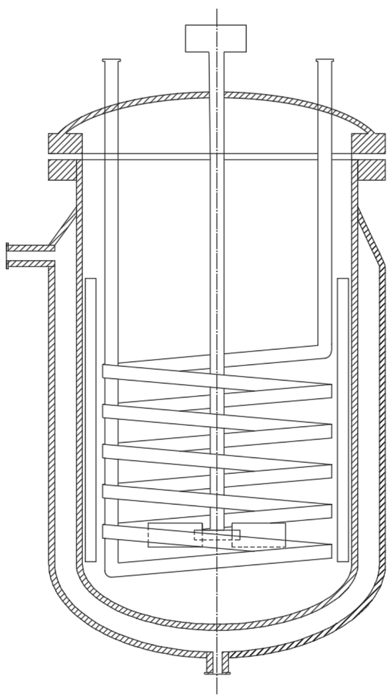


Figure 5.5. Batch pasteuriser. Jacketed stirred vessel with internal coil for heat transfer.

If the constrained problem cannot find a feasible jacket design, an internal coil (larger heat transfer surface) is designed. The resistance model is modified to represent the vessel-coil heat transfer (*Eq.D.33*). Thus, Chilton, Drew and Jebens correlation adapted to an internal coil is used to estimate h_0. The Dittus-Boelter model for heating non-viscous fluids flowing inside a tube in turbulent regime (Ocon and Tojo, 1980), with the addition of a non-straightness correction factor (McAdams,1942; Kern, 1983), computes h_{i}. The diameter and the maximum number of turns of the coil is set by the vessel diameter (see Section D.4.3) and the coil tube is assumed to be IPS 2”. The number of turns (N_{turn}) is the design variable that set the heat transfer surface needed for the heat supply. The minimum N_{turn} for the coil to satisfy the heat transfer requirements set by the energy balances is found by iteration, identifying the optimal design for the installation. When the coil design procedure cannot find a feasible solution, the algorithm designs a coil with the maximum permitted heat transfer surface, together with an additional external jacket to supply the rest of the energy needed.

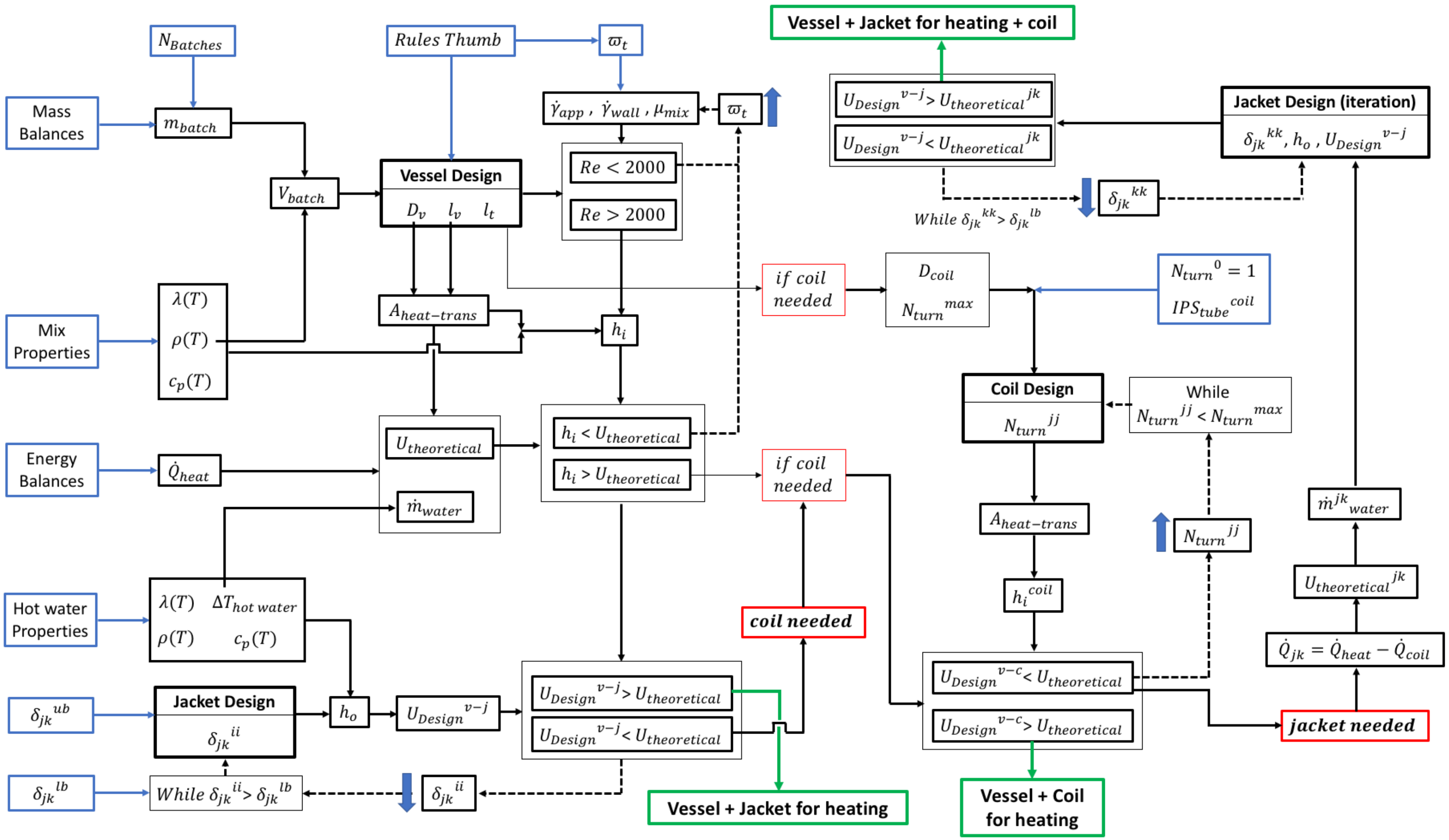


Figure 5.6. Heat transfer installation design for a bath pasteuriser. Blue squares represent input parameters. Green squares mean that the optimal solution has been found. Red frames indicate there is no solution within the set constraints and an alternative design is selected. Dashed arrows show iteration loops.

Continuous Pasteurisation (HTST)

High-volume pasteurisation is commonly performed using a plate heat exchanger (PHE). PHEs give improved heat transfer than tube counterparts when the heated/cooled fluid is viscous and operates at low pressures (Sinnott and Towler, 2013). Here, a PHE is designed for the ice cream continuous pasteurisation. The detailed procedure can be found in Appendix D, Section D.5.

Continuous pasteurisation allows a regeneration stage for economic and quality benefits. Energy savings up to 95 % have been recorded in literature when using regenerative pasteurisation (Mathisson, 2015). Here, the regeneration yield is a parameter fixed at 80% (Goff and Hartel, 2013). *Fig.5.7* depicts the three sections of the designed PHE, i.e. regeneration, heating and cooling. Each section will be designed following the procedure described in Section D.5. The number of plates (N_p) provide the heat transfer surface necessary for matching the energy balances. The heat transfer coefficient in the PHE is first calculated using the forced-convective heat transfer in conduits correlation (Ocon and Tojo, 1980).

Turbulent flow is advisable to improving the heat transfer (Žukauskas, 1994). A Re – defined for flow through the canal between two plates (defined further in *Eq.D.39*)– above 400 will ensure a turbulent flow for viscous liquids (Sinnott and Towler, 2013). Design variables are the plate size and the plate spacing. Smaller plates and a narrower gap between plates will increase Re value; but operating at very high Re would damage the mix emulsion (Goff and Hartel, 2013). An algorithm was developed for keeping the flow at Re=425. Decision variables are constrained to commercial values, e.g. plate width between 0.01m and 0.7m. *Fig.5.8* shows the routine that the algorithm follows for finding the optimal design parameters, i.e. those values that ensure the design meets the energy balance requirements while achieving the desired flow regime for quality control.

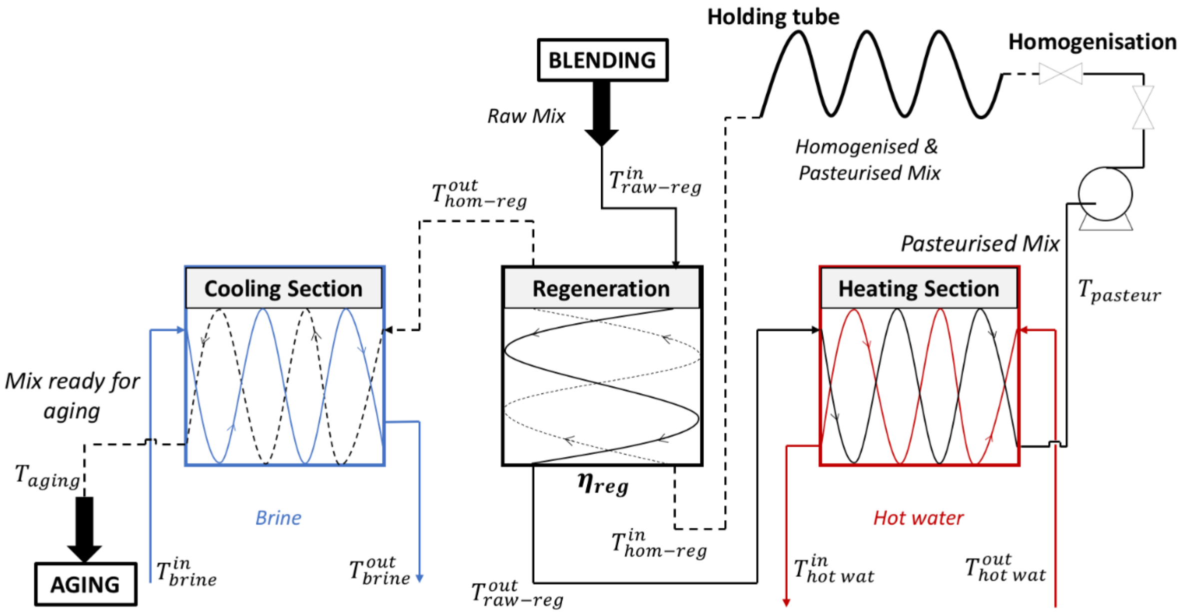


Figure 5.7. Continuous pasteuriser. Plate heat exchanger device with the different sections: cooling, regeneration and heating. It allows heat integration for energy saving. Solid lines represent raw mix, while dashed lines mean pasteurised and homogenised mix. The homogenisation stage takes places right after the mix heating.

A holding tube is also designed, placed after the homogenisation stage to ensure the mix stays at the pasteurisation temperature for the demanded time. The velocity through the holding tube must be set above 1ft/s (U.S. Department of Health and Human Services, 2017). A safety factor is added to the model, so the holding tube section has a flow velocity 20% above the minimum. The pasteurisation time then sets the length of the holding tube.

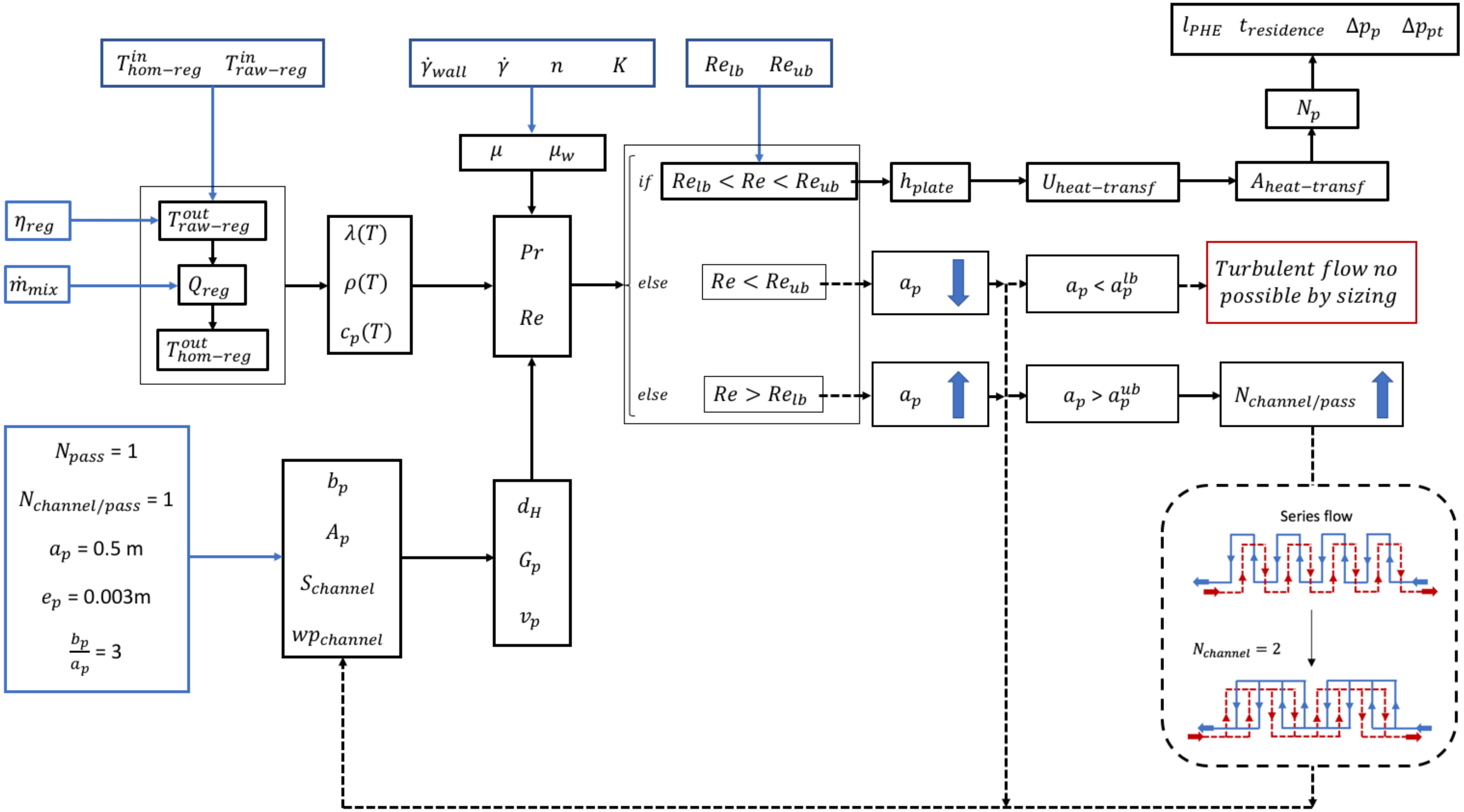


Figure 5.8. PHE design routine. Blue lines represent input parameters. Taken the regeneration yield as a parameter, the temperature profile is solved. Standard size for plate dimensions is chosen as the starting point. The optimal size of the plate and number of channels are adjusted so the flow regime is kept at the desired conditions for quality control, and the number of plates needed to provide the requested heat transfer surface is computed. Finally, the pressure drop at the designed PHE is calculated.

5.6.3.2. Dynamic freezing: Scraped surface heat exchanger (SSHE)

Freezing the flavoured mix is the next step in the process. A SSHE (see *Fig.5.9*) is the device selected for performing this operation (Arellano et al., 2013b). SSHE capacities can vary from 100 to 4500 kg/h per freezer barrel, it being possible to use several barrels in commercial models (Goff and Hartel, 2013). This flexibility makes it possible to use this type of equipment along the whole throughput range assessed here.

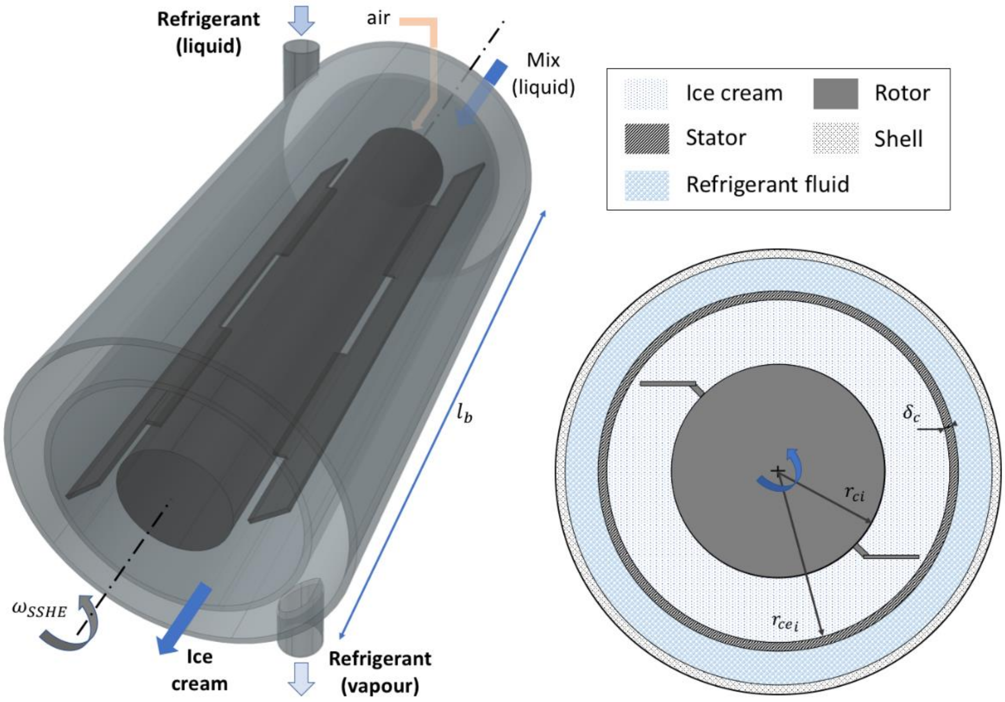


Figure 5.9. Representation of a SSHE used for ice cream dynamic freezing.

The refrigeration requirements ($\dot{Q}_{ref}$) are computed by mass and energy balances. Sensible and latent heat, viscous dissipation and scraping friction energy are the heat loads involved in the freezing process. The four thermal energies depend on the ice fraction, and hence the freezing temperature. *Eq.5.18* represents the total sensible and phase change heat removed. The heat capacity model considers all water as liquid (c_{p1}), until the temperature drops below T_{IF}, when ice contribution is added (c_{p2}). Viscous dissipation is heat generated from the work done by a viscous fluid on adjacent layers, due to the action of shear (Morini, 2013). Laminar mixing theory (Eq.5.19) is adopted to estimate viscous dissipation (Godfrey,1997; Bongers, 2006).

$$-\dot{Q}_{ref} = \dot{Q}_{sensible\ and\ latent} + \dot{Q}_{viscous} + \dot{Q}_{scraping} \qquad 5.17$$

$$\dot{Q}_{sensible\ and\ latent} = \dot{m}_{mix} \sum_j \int_{T_{in}}^{T_{IF}} c_{p1_j} dT + \sum_j \int_{T_{IF}}^{T_{out}} c_{p2_j} dT - L_f(T_{IF}) \int_{T_{FI}}^{T_{out}} x_w \frac{T_{IF}}{T^2} dT \qquad 5.18$$

$$\dot{Q}_{viscous} = \mu_{ic}\ \dot{\gamma}_{app} \dot{V}_b \qquad 5.19$$

$$\dot{Q}_{scraping} = c_1 {x_{ice}}^{c_2} \left(T - T_{ref}\right)^{\frac{5}{3}} N_{SSHE}\ l_b\ N_{blades} \qquad 5.20$$

Lastly, the large heat dissipation caused from scraping the frozen layer in contact with the cold wall, by the blades, is estimated using the empirically derived equation –*Eq.5.20*– proposed by Bongers (2006). Many authors estimate the scraping dissipation as 50% of the heat removed in the SSHE (Schwartzberg, 1990; Hartel, 1996; Russel et al., 1999; Bongers, 2006; Bayareh et al., 2017). Based on this approach and due to the confidentiality of the experimental constants in *Eq.5.20* (c_1 and c_2), parameter estimation is done to find those values that fit the previous assumption.

The procedure for the design of the SSHE follows the same steps as the previous equipment. Energy removal computed by the energy balances is related to the variables of design using the general equation for heat transfer across a surface, referred to the external surface of the annulus. The resistance model comprises all the mechanisms involved in freezing: convection, conduction and fouling resistances.

$$\frac{1}{U_b} = \frac{r_{ce_i}}{r_{ce_o} h_{e_{ref}}} + \frac{1}{f_{ref}} \frac{r_{ce_i}}{r_{ce_o}} + \frac{(r_{ce_i}) \, ln\left(\frac{r_{ce_o}}{r_{ce_i}}\right)}{\lambda_{stainless\ steel}} + \frac{1}{f_{ic}} + \frac{1}{h_{i_{ic}}} \qquad 5.21$$

Convection on the refrigerant side is estimated using the correlation developed for the condensation of liquids outside horizontal tubes (*Eq.5.22*) (Sinnott and Towler, 2013). To predict the heat transfer coefficient of the ice cream, the correlation developed by Boccardi et al (2010) for the production of ice cream in a SSHE, following Skelland's (1958) procedure, is applied (*Eq.5.23*).

$$h_{e_{ref}} = 0.95\,\lambda_L \left[\frac{\rho_L(\rho_L - \rho_V) g}{\mu_L\, \Gamma_h}\right]^{1/3} ;\ \Gamma_h = \frac{\dot{m}_{cond}}{l_b} \qquad 5.22$$

$$Nu = \frac{h_{i_{ice\ cream}} D}{\lambda_{ice\ cream}} = \qquad 5.23$$

$$= 0.208 \left(\frac{\rho_{ic}\, v_{ic}{}^{barrel}\, 2r_{ce_i}}{\mu_{ic}}\right)^{0.7192} \left(\frac{cp_{ic}\, \mu_{ic}}{\lambda_{ice\ cream}}\right)^{0.783} \left(\frac{\varpi_{SSHE}\, 2r_{ce_i}}{v_{ic}{}^{barrel}}\right)^{0.406} \left(\frac{2r_{ce_i}}{l_b}\right)^{0.523}$$

$$v_{ic}{}^{barrel} = \frac{\dot{V}_b}{c_b\, \pi\, r_{ce_i}{}^2} \qquad 5.24$$

The design variables will be the radius of the external cylinder comprising the annulus, the length of the barrel, the free flow section percentage and the rotational speed of the dasher. Sizing variables are constrained to commercial dimensions for SSHE, i.e. 0.05 m < r_{ce_i} < 0.15 m and 0.50 m < l_b < 10.00 m. A high-displacement barrel, with a free crossflow section between 15-30% is chosen to have a thin layer of mix flowing inside the unit. The thin layer allows faster freezing to a lower temperature, producing smaller ice crystals, a higher degree of fat agglomeration and strong air bubbles, i.e. increased quality (Tharp and Young, 2013; Goff and Hartel, 2013). No radial temperature gradient is assumed. Finally, the rotational speed will range between 100 rpm and 200 rpm to avoid high nucleation of the ice crystals and high energy dissipation (Goff and Hartel, 2013).

An algorithm is developed for finding the best design to fit the energy balance (*Fig.5.10*). Mass and energy balance, refrigerant and mix properties, inlet and outlet freezing temperatures and boundary vector are inputs of the problem. A maximum absolute error of 5% between the refrigerating requirements from the energy balance (target) and the provided one by SSHE design is set. A maximum capacity per barrel is set at 3 m^3/h (Goff and Hartel, 2013). When the production exceeds the maximum capacity of the group of barrels, an additional barrel is added, and the ice cream flow splits among the whole number. If there is no feasible design for the refrigeration requirements, the maximum barrel capacity is reduced step-by-step (-0.1 m^3/h per step). At each new condition point, the algorithm tries to find a feasible design until the problem is solved.

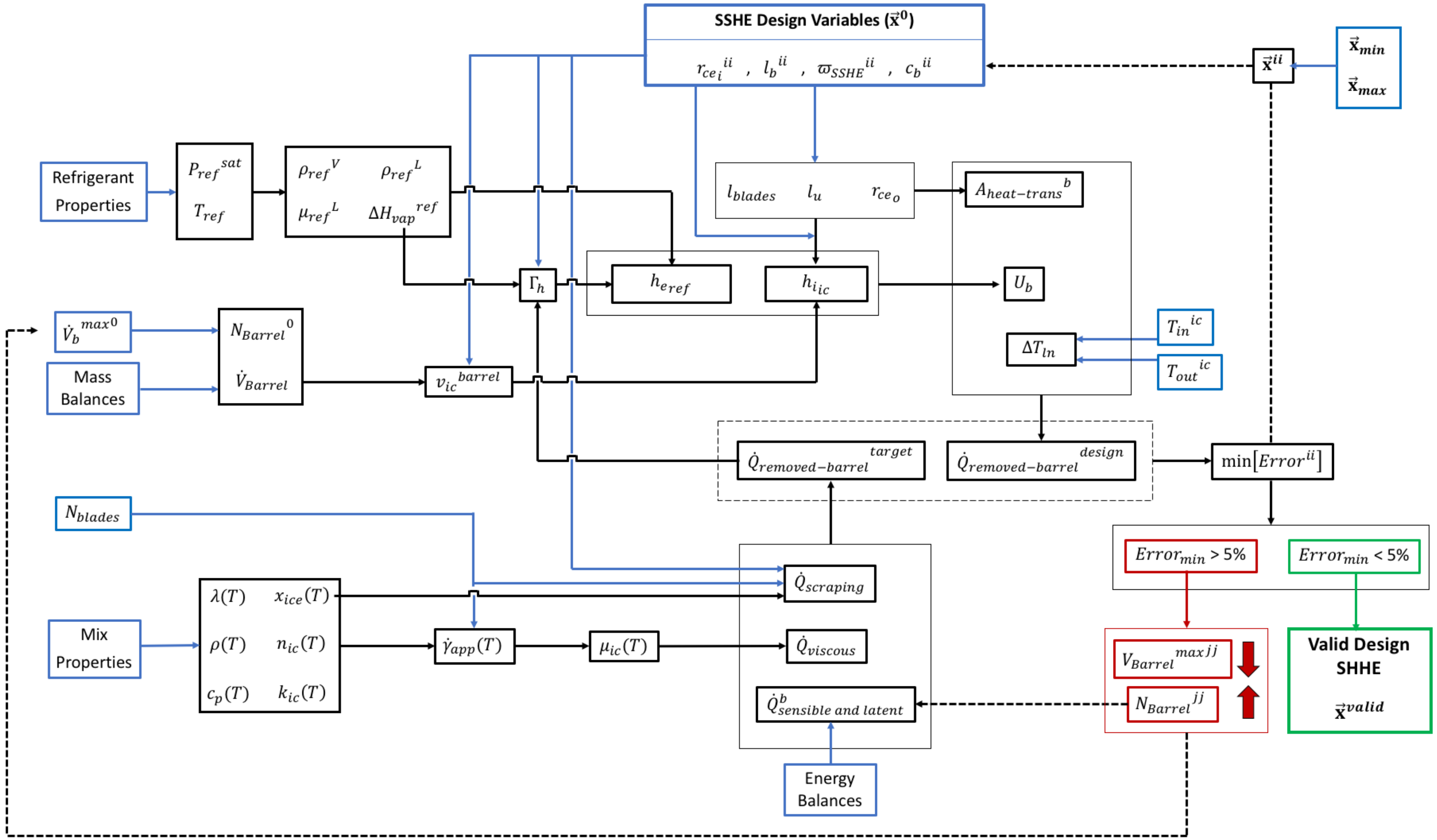


Figure 5.10. Scheme representing the computational routine for the design of the continuous freezer (SSHE). Blue lines are the input parameters; green and red squares represent a feasible and unfeasible solution respectively. A fist loop minimises the error between the targeted heat removal of the energy balances and the one achieved by the constrained design. If no feasible solution is found, the ice cream flow through the barrel is reduced with a new barrel addition and the optimisation calculations are repeated.

5.6.3.3. *Hardening and storage*

The last step that involves heat transfer is hardening. No design is carried out here. A commercial hardening tunnel is used for blast freezing of the ice cream packages. The maximum hourly production is set by the manufacturer, so a new unit is added when that capacity is exceeded. The refrigeration energy required at this stage will be computed by the energy balances, involving sensible and latent heat exchanges.

Storage of fresh ingredients must be in a chilled room to avoid spoiling and ensure food safety. The volume of the chilled room is calculated from the area that the storage recipients occupy (lay-out of the plant) and the resulting maximum height. The final product is stored in a freezing warehouse with enough capacity for one month of production (Goff and Hartel, 2013). Evans et al. (2011) and Tassou et al. (2008) provide an average annual energy use of chilled and frozen stores per m^3 of volume, used here to compute energy consumption.

5.6.4. *Artisan process modelling*

The unit operations of the process are carried out using different pieces of equipment for each scale based on the artisanal process (see *Table 5.5*). All instrument specifications are indicated by the manufacturer (i.e. production capacity, power consumption and dimensions). The maximum production for the processing line corresponding to each method is computed here as:

$$t_{batch} = 3600 \times \left(N_{batch-hour}{}^{unit}\right)^{-1} = 3600 \left[\frac{N_{unit}\dot{M}_{unit}}{F_V\, V_{unit}\, \rho_{ic}}\right]^{-1} \qquad 5.28$$

$$\eta_{ref} = \frac{Q_{ref}{}^{EB}}{(N_{unit}P_{unit}t_{batch}) \times COP_{ref}} \qquad 5.29$$

First, the batch size of any unit is settled based on its capacity. The residence time for a batch in a piece of equipment (t_{batch}) is defined either by regulations –e.g. pasteurisation– or heuristic data –e.g. mixing and ageing. When heat transfer is involved, the residence time is calculated –see *Eq.5.28*– using the volume capacity and the production rate provided by the manufacturer when available (e.g. batch freezer). Conversely, energy balances and equipment efficiencies are used to compute the heating/cooling time for those units that involve heat transfer and whose production capacity is unknown (i.e. pasteuriser and ageing vat in DM).

For the pasteurisation stage using a pot and an induction hob (HM and FI scales), the mix will be first cooked at low power –$F_{low-power}$ = 1/3– to avoid damage until the pasteurisation temperature is reached, and then is kept for the pasteurisation time. Heating of the pot (stainless steel), radiation and convection heat dissipation are accounted as energy losses at this stage. The time used for pasteurising a batch of mix is then given by *Eq.5.30*.

$$t_{past-stage}{}^{HM} = \frac{F_V\, V_{pot}\, \rho_{mix} \int_{blend}^{T_{past}} C_{p_{mix}} dT + C_{p_{ss}} M_{pot}\left(T_{past} - T_{blend}\right)}{\eta_{stove}\, \eta_{cooking}\, F_{low-power}\, P_{stove}} + t_{past} \qquad 5.30$$

The maximum number of batches and volume of mix that can be produced at each stage, during a workday, are estimated considering the time window available for a non-overlapping process. The limiting stage is thus identified setting the maximum quantity of product that can be produced in a day. Mass balances are then performed on a daily time basis to calculate the raw materials that a single production line requires. A material waste factor accounts for losses after each batch. Finally, the ratio between the theoretical energy transfer resulting from the energy balances and the equipment input power given by the manufacturer will allow to compute the efficiency of each unit.

Once the daily production of a single facility has been estimated, the annual production can be easily assumed. The number of facilities to duplicate the plant production of a settled production rate is later computed.

5.6.5. Energy consumption and carbon footprint of the processes

For artisan manufacturing, the process is fully electric based. The energy use per batch is calculated from the sum of the power consumption of each equipment, using the residence time previously computed and the power input given by the manufacturer. Conversely, industrial manufacturing of ice cream involves further calculations. The sources of energy assumed are electricity for processing equipment power, pumping energy, refrigerated storage and cooling/freezing equipment, and natural gas –auxiliary water heating at the pasteurisation stage.

Experimental correlations relating the Power, Froude and rotational Reynolds numbers are used to estimate power consumption in stirred tanks. Fully baffled laminar flow is assumed (Sirasitthichoke and Armenante, 2017; Coulson et al., 1999). Qin et al. (2006) developed a similar equation for ice slurries refrigeration involving change of phase in a SSHE (*Eq.D.43-44*).

Six pumps are accounted within the process flowsheet (see *Fig.5.2*). The first balances the pressure drops of the raw mix entering the regeneration and heating sections of the PHE (if applies). The second provides the power to reach the pressure for homogenisation of the pasteurised mix, while a third balances the head loss at the regeneration and cooling sections of the pasteurised mix and fills the ageing tank. The fourth pump allows the flavoured mix to reach the operating pressure of the freezing mix, whereas the last two are involved in the brine and hot water cycles used for heat transfer in the PHE. The shaft work consumed by each pump (P_{pump}) is calculated from Bernoulli equation, once the pressure loss has been estimated. Pumping losses (η_{pump}) and electric engine internal losses (η_{rotor}) are considered (Sinnott and Towler, 2013).

$$P_{pump} = \left(\frac{1}{\eta_{rotor}\,\eta_{pump}}\right)\left(\dot{m}\,\frac{\Delta p}{\rho(T)}\right) \qquad 5.31$$

Two refrigeration cycles with different refrigerants have been designed. Ammonia is directly used for freezing the ice cream at the SSHE and for cooling the brine cycle due to its zero environmental impact. Refrigerant R404 a is used at the hardening tunnel and the freezing warehouse where a lower freezing temperature (below -25˚C) must be reached. The shaft work (P_{ref}) is calculated using *Eq.5.32*

$$P_{ref} = \frac{\dot{Q}_{ref}}{COP_{ref}} = \frac{\dot{Q}_{ref}}{\eta_{carnot}\left(\dfrac{T_{ref}{}^{evap}}{T_{ref}{}^{cond} - T_{ref}{}^{evap}}\right)} \qquad 5.32$$

Finally, the fuel (natural gas) mass flow ($\dot{m}_{gas}$) required as energy supply within the hot water cycle is computed as follows:

$$\dot{m}_{gas} = \left(\frac{1}{\eta_{boiler}}\right)\frac{\dot{Q}_{past}}{LHV_{gas}} \qquad 5.33$$

Greenhouse gas emissions (GHG) is the indicator used here for estimating the carbon footprint of the process. It is computed using each energy source demand and the corresponding energy conversion factors: 0.20463 $kgCO_2e/kg$ for natural gas and 0.41205 $kgCO_2e/kg$ for electricity (Government of United Kingdom, 2019c). No refrigerant leaks are assumed at the mechanical refrigerators and chilling equipment for both industrial and artisan processes.

5.6.6. Economic evaluation

Cost estimation has been carried out following the procedure developed in Chapter 3. The Individual Factors method was used to calculate the annual operating cost and total capital required at each scale. *Tables A.7* and *A.8* in Appendix A list the individual factors assigned for each manufacturing scale.

The operating cost is defined as the expenditure incurred by the manufacturing process operation and management, as discussed in Chapter 2. It comprises variable (e.g. raw materials, utilities, packages) and fixed cost (e.g. depreciation of instrumentation, rent fees, labour, maintenance) costs. The former increases linearly with the production rate, while the latter scales with the size of the constructed facility and is constant once the facility is built. The particular characteristics of each designed scale will affect the operating cost. The total capital represents the initial investment necessary to build the facility and start-up the process–e.g. industrial machinery cost, see correlations of *Table D.5*. The outlay is done only once.

Uncertainties are introduced in both operating cost and capital calculations to provide a trust region for the given values (see Chapter 3). Peters and Timmerhaus (2003) recommend an asymmetric spread for the capital cost estimation, increasing direct capital 40% for the upper bound and reducing 20% for the lower bound. With regard to production cost, marketing and raw material prices (*Table D.6*) comprise the highest uncertainties. The upper bound is represented taking the marketing individual factor as 22% (Peters and Timmerhaus, 2003) –the standard value is 15%– and increasing the raw material retail price by 15% (Nakamura, 2008). Conversely, the lower bound assumes a marketing individual factor of 5% and a discount of 21% in the standard retail price of raw materials to eliminate retail profits (Chidmi and Murova, 2011; Jindal et al., 2018).

The net profit evaluates the profitability of each scenario. The calculation of the Net Profit per facility (Π_{fac}) for the artisanal manufacturing scale will indicate the feasibility and motivation for the freelance agents to develop this business. *Eq.5.34* shows how to calculate this value. It is assumed that all units produced are sold and the sales revenue is equally divided among all the facilities. Taxes ($\tau_{corp}, \tau_{VAT-ic}$) are deducted from the gross profit, which is the difference between sales revenue –amount of product sold (q_{ic}) at price p_{ic}– and operating cost (OC_{ic}).

$$\Pi_{fac} = \left(1 - \frac{\tau_{corp}}{100}\right)\left[\left(1 - \frac{\tau_{VAT-ic}}{100}\right)(q_{ic}\, p_{ic} - OC_{ic})\right] \times \left(\frac{1}{N_{facilities}}\right) \qquad 5.34$$

5.7. Results and discussion

The modelling tool is used to characterise multiple ice cream manufacturing scenarios at different production scales. This section is organised as follows. First the effect of the formulation on the thermal properties is assessed. Next, the effect of the manufacturing scale on the operating cost for a range of throughputs is evaluated. The identification of the operational regions for each manufacturing scale is later carried out, followed up by the total capital profile and the effect of production rate on the energy consumption. Finally, a case study where each manufacturing scale supplies an ice cream demand similar to the UK scenario is performed.

5.7.1. Thermal properties behaviour for the different mix formulations

The model developed in Section 5.4 is applied here for the formulations characterised in Section 5.3. Thermophysical properties and density profiles, showing their sensitivity to temperature changes over the range of operation, is shown in *Fig.5.11*.

Fig.5.11a shows the specific enthalpy profile. For temperatures above the initial freezing temperature, the specific enthalpy follows a similar trend. Standard ice cream results are very similar to those of Cognè et al. (2013). Premium ice cream has less water added for the mix preparation, but the overall water content is higher. Thus, for the mix to achieve a certain temperature below T_{IF}, more water has to freeze (see *Fig.5.11b)* and a higher enthalpy must be extracted. This performance is enhanced by the use of Miles model (Miles et al., 1983), which does not consider a bounded –unfrozen– water mass fraction in the calculations, so all the water is subjected to freeze.

Three different thermal conductivity values are displayed in *Fig.5.11c*. The highest values are reached by the non-overrun mix, showing an increasing trend responding to the ice phase growth. The higher water content of premium ice cream allows higher values to be reached. When air is incorporated the lower thermal conductivity of air bubbles, compared to the one of ice, decreases the thermal conductivity of the ice cream. For the continuous phase, the reduction in water content during freezing lowers thermal conductivity for this phase. Results are similar to Cognè et al. (2013) and Hernández et al. (2018) experimental data.

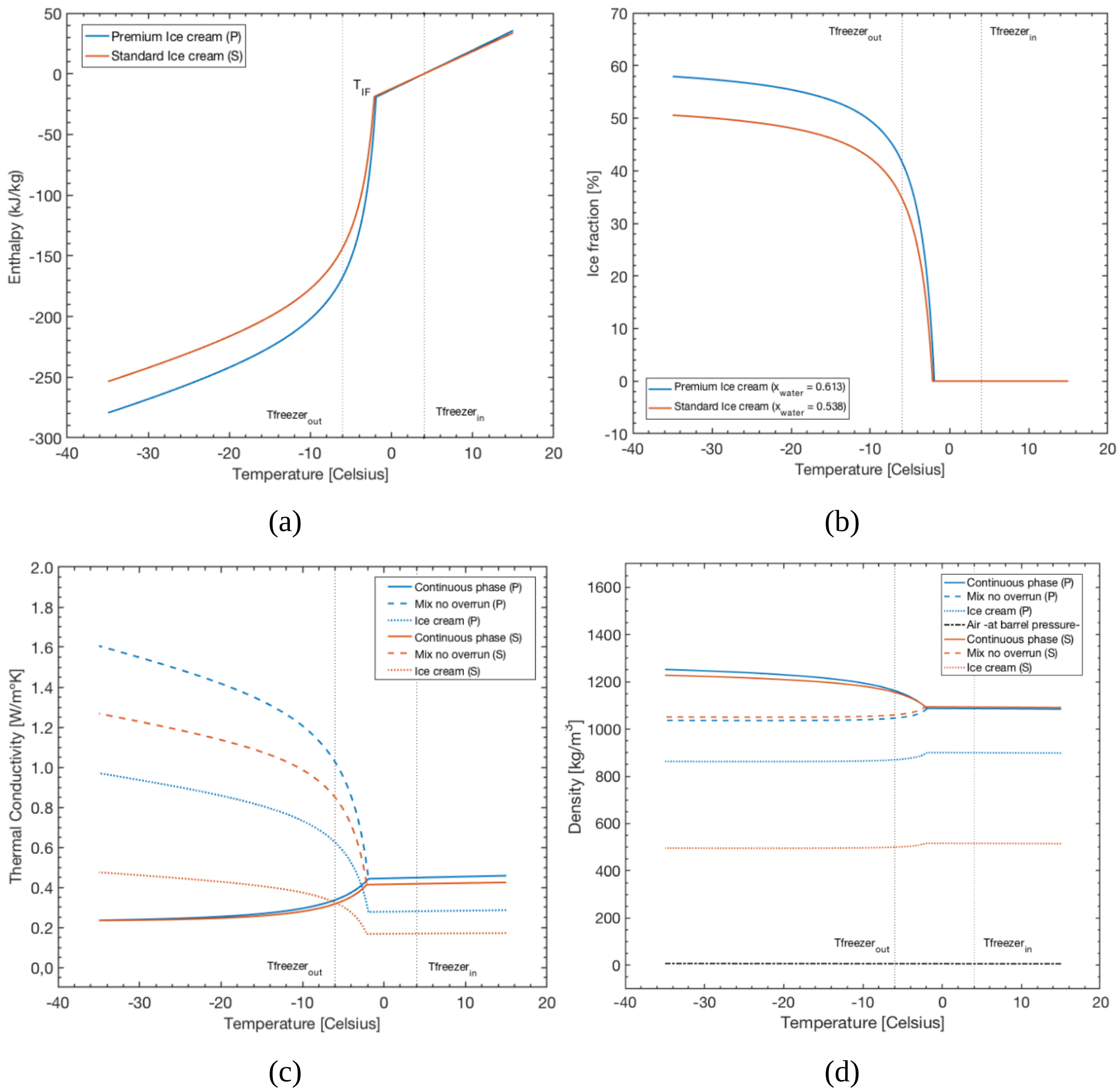


Figure 5.11. Thermal properties of standard (S – orange) and premium (P – blue) ice cream formulations: (a) Enthalpy (b) Ice weight fraction curve (c) Thermal conductivity and (d) Density. Premium ice cream has more overall water content, so more energy is required to lower the temperature. The higher water content increases the thermal conductivity for both the aerated (ice cream) and non-aerated (no overrun) mix. The density of the premium ice cream is higher due to

the lower air content. For non-aerated mix at the same temperature, standard formulation has a slightly higher density as less ice is formed.

Finally, the density is evaluated. Continuous phase shows the highest density, that increases below T_{IF} with lower temperatures when the aqueous solution concentrates due to the solvent freezing. Conversely, the density of non-overrun ice cream decreases as ice is forming. The premium formulation, with a smaller overrun and thus less air content, has a higher density than its standard counterpart (see *Fig.5.11d)*.

5.7.2. Operation cost of ice cream process at multiple manufacturing scenarios

A comparison of the five manufacturing models –HM, FI, DM, SP and MP– is done here. Premium ice cream manufacturing, sold in packages of 500 ml, is chosen as the benchmark case study within the results. The alternative packaging and the standard ice cream production (vanilla flavour) will be used as a sensitivity analysis for the cost estimation.

The maximum capacity of single facility is 3.0 kg/h for HM, 8.7 kg/h for FI and 21.8 kg/h for DM. Industrial manufacturing lines comprise equipment with flexible designed capacities, so there is not any maximum capacity set by the design. The unit operation that limits a single facility daily production, for each artisan-based method, is detected:

- HM: *freezing stage*. The freezing capacity of the ice cream maker constrains the production of a HM processing line.
- FI: *pasteurisation*. Traditional cooking pasteurisation is the production constraint, as the 3-in-1 ice cream machine overcomes the previous limitation.

- DM: *ageing*. The modular processing line finds a restriction in the ageing vat capacity. An additional unit would double the output of this facility.

Within this section, the production rate is set as an independent variable ranging from 0.01 kg/h to 50,000 kg/h. All the manufacturing scenarios are modelled over this scale to check variations in the performance of the operating cost.

A similar behaviour that of the previous food items evaluated (see Chapter 3 and Chapter 4)– is found for ice cream manufacture (*Fig.5.12*). Artisan-based processes have discontinuities caused by the integer constraints. When a set of facilities reaches maximum capacity, a small increment on the production rate requires an additional facility, and thus higher fixed costs cause a step in the unit cost curve. These steps are wider for a higher fixed cost regarding a new facility addition –i.e. DM with high management– and at low throughputs. The effect decreases at greater throughputs, as the increment in fixed cost is spread among a higher number of units produced (effect of the economy of scale). SP and MP scenarios do not show this as the integer constraints are limited to a few pieces of equipment.

For the lowest throughputs at each method, the highest costs are found due to the larger fixed cost/variable cost ratio. The smallest scales, comprising lesser fixed cost, can be competitive at lower throughputs. Thus, HM is the manufacturing scale that provides affordable costs at production rates of 1 kg/h, while FI increases the cost due to the rent for a food incubator. DM can offer very low costs for ice cream manufacture, even below HM results when low management constraints are assumed.

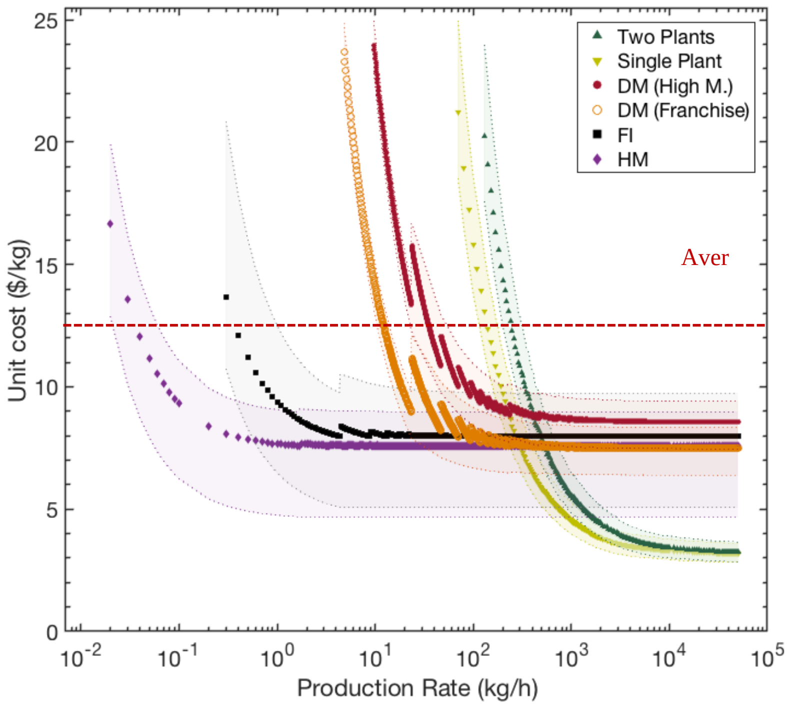
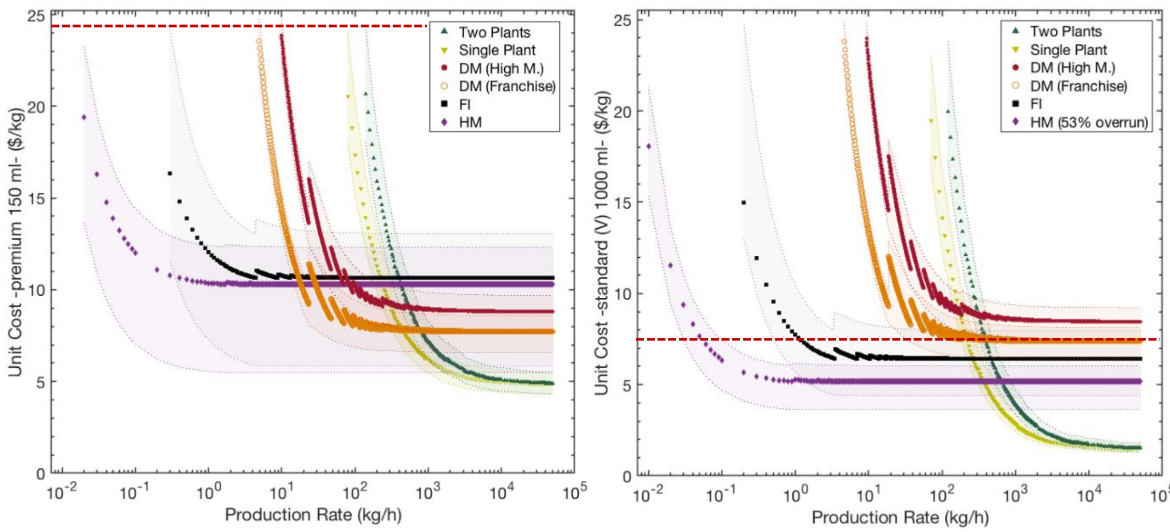


Figure 5.12. Variation of the unit cost ($/kg) for different manufacturing scales in the production of premium ice cream sold in 500 ml units. The market price per kg assumed for this product is obtained from the average price per unit (5 £/unit) when comparing the four most important supermarkets of UK. It is 12.4 $/kg, after taxes discount (20%). Shaded areas represent the trust region set by the uncertainties.

The effect of the packaging format in premium ice cream manufacturing, when changing from 500 ml tubs to 150 ml tubs, is important. An increase in the unit cost for all scales can be observed when comparing *Fig.5.12* and *Fig.5.13(a)*. For industrial manufacturing, the production costs rise by 50%. Packaging cost increases by 6 times, while management cost increases by 40% due to the higher number of units sold. The higher capital required has an indirect effect on the production cost. Working capital (70% higher) and machinery (16% more expensive) increase financial and depreciation costs respectively. For artisan-based scales, the unit cost for the two smallest scales (HM and FI) increases above that of DM, which shows a loss in competitivity for these two methods. Despite unit costs being sensibly higher for the three scales, DM lines achieve lower unit cost when the ice cream is packaged in 150 ml tubs. The management cost assumptions for HM and FI exemplars, calculated as a multiplier of sales revenue following the 'gig economy' model, is the main factor causing this behaviour. The higher selling price for the smallest tubs and the higher number of units double the management cost for these two scenarios. Conversely, for DM only the additional cost of purchasing more packs when selling the same volume of product, increases the operation cost.



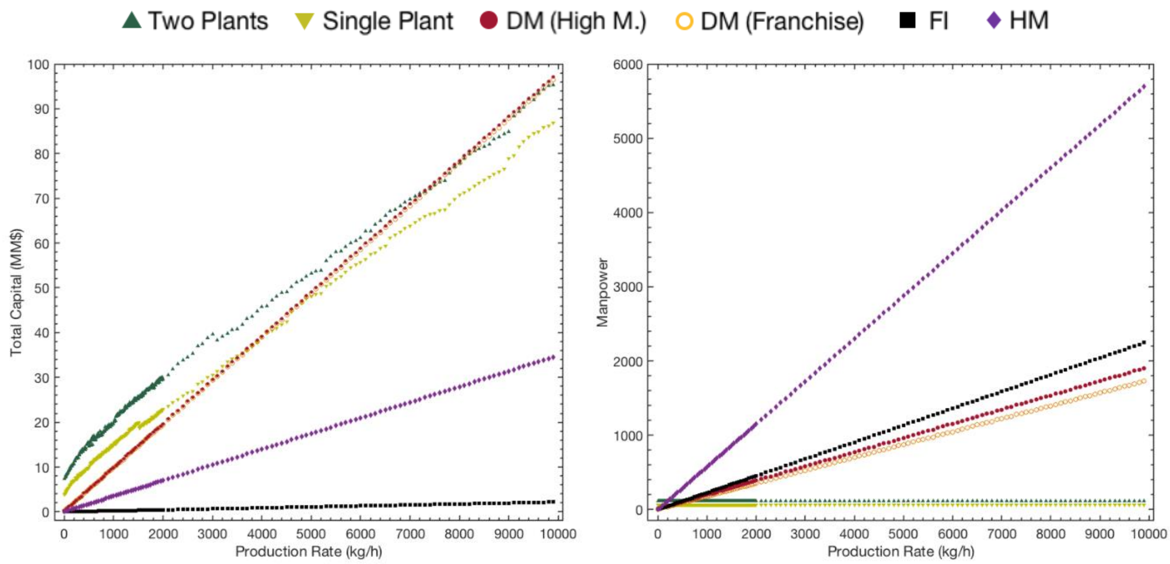
(a) (b)

Figure 5.13. Variation of the unit cost ($/kg) for different manufacturing scales in the production of (a) Premium (HQ) ice cream sold in 150ml units and (b) Standard ice cream sold in 1000ml units. The market prices assumed for these products are obtained from the average prices per unit (3 £/unit and 3.5 £/unit) when comparing the four most important supermarkets of UK. They are 24.3 and 7.4 $/kg respectively, after taxes discount (20%). Shaded areas represent the trust region set by the uncertainties. The higher ratio of raw material and packages cost within the total operating cost makes uncertainties wider for the premium ice cream sold in small tubs when compared to standard ice cream.

Standard ice cream formulation comprises cheaper raw materials and greater overrun, so the volume of final product obtained from a certain volume of plain mix is considerably higher. *Fig.5.13(b)* shows unit cost changes with throughput for manufacturing standard ice cream. Centralised manufacturing reduces the production cost by 50%, caused from the great savings in raw materials, having the rest of the cost items more similar values. A larger number of facilities is required to produce the same mass output in artisan scales, due to the lower density of the standard ice cream and the invariant volume capacity of the instrumentation. DM costs are similar to premium ice cream manufacturing and cannot compete with HM and FI. The increase in the number of facilities imply higher labour, investment and management costs, that balance the savings in raw materials. For HM and FI freelance-based scenarios, the effect of increasing the numbers of facilities does not involve higher unit cost (32 % and 20% respectively less than premium ice cream sold in 500 ml tubs) but the profitability per facility drops considerably. The difference between the two smallest scales is enhanced by the higher share that the food incubator's fee has in the overall cost, as more facilities are required for producing the same mass of ice cream, while HM does not incur any additional cost.

5.7.3. Influence of the manufacturing scale on the total capital and labour

It is useful to compare the total investment required to start the commercial for the different manufacturing methods described here. Capital required represents a barrier for companies to start a business and supply an unsatisfied demand. Thus, low capital needed represents a low investment risks that could attract potential investors. *Fig.5.14(a)* shows the growth of the total capital with production rate, for all the scales.



(a) (b)

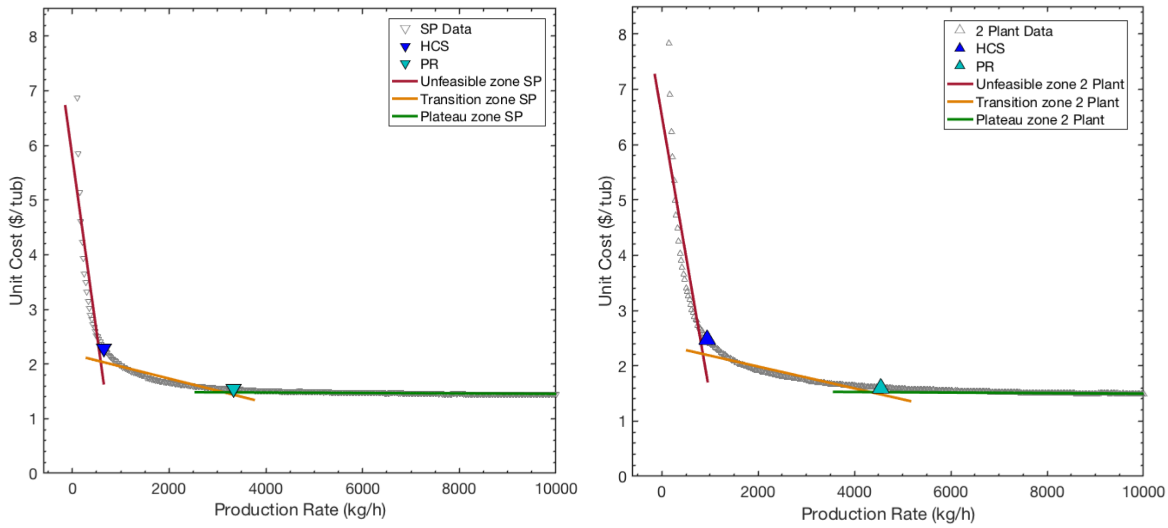
Figure 5.14. Total Capital (a) and Manpower (b) results for the four manufacturing scales.

Artisan manufacturing scales, such as HM and DM, show a linear increase in capital with production rate, and hence the number of facilities in the scenario. The lowest investment is observed in FI because the assets here belong to an external agent and are rented by the freelance workers, so only working capital is needed for starting-up the business. HM uses common instrumentation that the worker already owns, so there is also no initial capital that must be invested. However, the value of the equipment is accounted here as it is worker's property and it will need to be replaced at the end of its lifespan (depreciation as production cost item). For DM scale, management does not influence total capital. Modular production lines are cheaper than high-volume plants at production rates but become more expensive when a certain throughput is reached, e.g. for a production of 3700 kg/h, 158 DM facilities requires a similar investment than a single plant with the same output. Industrial manufacturing shows a stepped progression resulting from the integration of additional equipment, when maximum capacities are reached. If the production is divided in two operating plants, the total capital follows a parallel trend to SP, with an averaged addition of 8 MM$.

The required manpower, representing job creation opportunity, is a social impact indicator for each scenario (Hale et al., 2019; Dufour, 2019). Industrial manufacturing scenarios follow *Fig.A.1*. organisation chart for calculating personnel. SP has the lowest number of workers (60) required for the operation mode selected (16h/day), independently the capacity of the production line. Each additional plant increases the number of workers by 54, assuming the senior management board is shared. This is in contrast to the manpower needed for artisanal manufacturing scenarios, which is generally higher. *Fig.5.14(b)* shows the different labour requirements for all scales in the chosen production range. The rate of growth for artisan-based scenarios is inversely proportional to facility size. Thus, freelance exemplars (HM and FI), comprising one worker per facility, show the highest manpower. DM facilities increase the production per worker with the use of specialised equipment, so fewer workers are needed. High management assumptions include more personnel, organised as shown in *Fig.A.2*, but still comprise less personnel than FI.

5.7.4. Data trend analysis of unit cost: identification of operational regions

The cost data provided by the modelling tool is analysed to identify trend variations in the production cost, following the methodology set in Chapter 3. Here, the cost per ice cream tub is assessed and displayed. Optimal partitioning is applied to detect the high change in slope (HCS) within the data set (Killick et al., 2012; Jackson et al., 2015). Due to the discontinuities in the data, the finite difference method (Fornberg, 1988) has been used to evaluate the derivative of the curve at each data point, and thus identify the plateau point (PR) for each manufacturing scale. The criterion assumed here sets the plateau when the derivative values are continuously below 10^{-4} \$ kg^{-1}/ kg h^{-1}. *Fig.5.15* and *Fig.5.16* displays HCS and PR points for all the manufacturing scales.



(a) (b)

Figure 5.15. Identification of the three different operation regions defined in this work for industrial ice cream manufacturing carried out in (a) Single plant manufacturing and (b) Two Plants manufacturing.

Taking *Fig.5.14(a)* as an example, the unit cost curve is divided in three recognisable sections:

- *Unfeasible zone*: located at lower throughputs than HCS, comprises the highest slope. Operating within this region is not advisable as productivity is very sensible to capital injection, i.e. slightly higher capacities greatly reduces operating cost.

- *Transition zone*: a production scenario located between the two characteristic points can be feasible as long as it is profitable. Significantly higher capital is needed for the construction of a higher-capacity plant, without remarkable advantage in cost efficiency. The size chosen will depend on the available capital and the existing market opportunity.
- *Plateau zone*: for production rates above PR, the operating costs reach a plateau so a higher capacity plant will require more initial investment without any further cost effectiveness. The economy of scale has no effect, so the benefits of a larger plant is caused only by increasing sales revenue.

Table 5.6 shows the value of HCS and PR points, previously defined, and the linear fitting of each operating region, for all the scales. The characterisation of the three operating regions for each manufacturing scale are represented in *Fig.5.15* and *Fig.5.16*. The former compares the unit cost of a single plant and two plants. A single plant with a capacity below 650 kg/h –i.e. unfeasible zone– will not operate with an advisable cost efficiency, while larger plants above 3325 kg/h –i.e. plateau zone– will not gain scale effectiveness. Both HCS and PR are found at a higher throughput for a two-plants scenario. A longer transition region is also observed, with feasible throughputs between 950 kg/h to 4550 kg/h.

Fig.5.16 provides the same information for the decentralised manufacturing options. Higher capacity per facility requires higher throughputs for feasible scenarios. Thus, *Fig.5.16(a)* shows that HM should produce more than 0.2 kg/h (the end of the unfeasible zone) while maximum cost efficiency is achieved when more than 4.4 kg/h are produced. One kitchen (max production of 3 kg $h^{-1}facility^{-1}$) can reach the feasible range, while a minimum of two kitchens is needed for operating within the plateau region. For FI,

Fig.5.16(b) shows that the transition zone starts at 1.1 kg/h, so one facility (max of 8.6 kg h^{-1}facility^{-1}) can be feasible. The cost per unit produced decreases slowly until the plateau is reached at 73 kg/h. Nine food incubators are needed to achieve this. Finally, feasible operation for DM requires production rates above 43.5 kg/h, increasing the lower bound to 90.7 kg/h when high management costs are assumed (*Fig.5.16(c)*). DM has a maximum production per facility of 21.8 kg h^{-1}facility^{-1}, so two and five manufacturing sites are respectively required. The highest cost efficiency of this scale is reached with throughputs higher than 671 kg/h (31 facilities) for franchise model and 1353 kg/h (63 facilities) if the corporation model is assumed (*Fig.5.16(d)*).

Table 5.6. High change on slope (HCS) and plateau reaching (PR) points, defined in section 5.7.4, for the manufacturing of premium ice cream sold in 500 ml tubs. X-axis coordinate (throughput – kg/h) and y-axis coordinate (unit cost – $/tub) are given. The linear fitting for each operating region, shown in *Fig.5.15* and *Fig.5.16*, is also listed below.

	Unfeasible section		HCS	Transition section		PR	Plateau section	
	slope	intercept	(kg/h) ($/kg)	slope	intercept	(kg/h) ($/kg)	slope	intercept
HM	-20.63	6.16	0.14 3.76	-0.033	3.35	4.4 3.25	-9.94 e-09	3.25
FI	-2.98	6.77	1.1 3.96	-0.001	3.49	73 3.43	-2.29 e-07	3.43
DM *(Low M.)*	-0.07	6.29	43.5 3.63	-4.12 e-04	3.46	671 3.25	-4.68 e-06	3.24
DM *(High M.)*	-0.03	6.88	90.7 4.18	-2.07 e-04	3.93	1353 3.71	-6.38 e-06	3.72
SP	-6.39 e-03	5.78	650.0 2.29	-2.21 e-04	2.18	3325 1.55	-3.86 e-06	1.49
2P	-5.05 e-03	6.52	950.0 2.5	-1.98 e-04	2.38	4550 1.60	-4.99 e-06	1.55

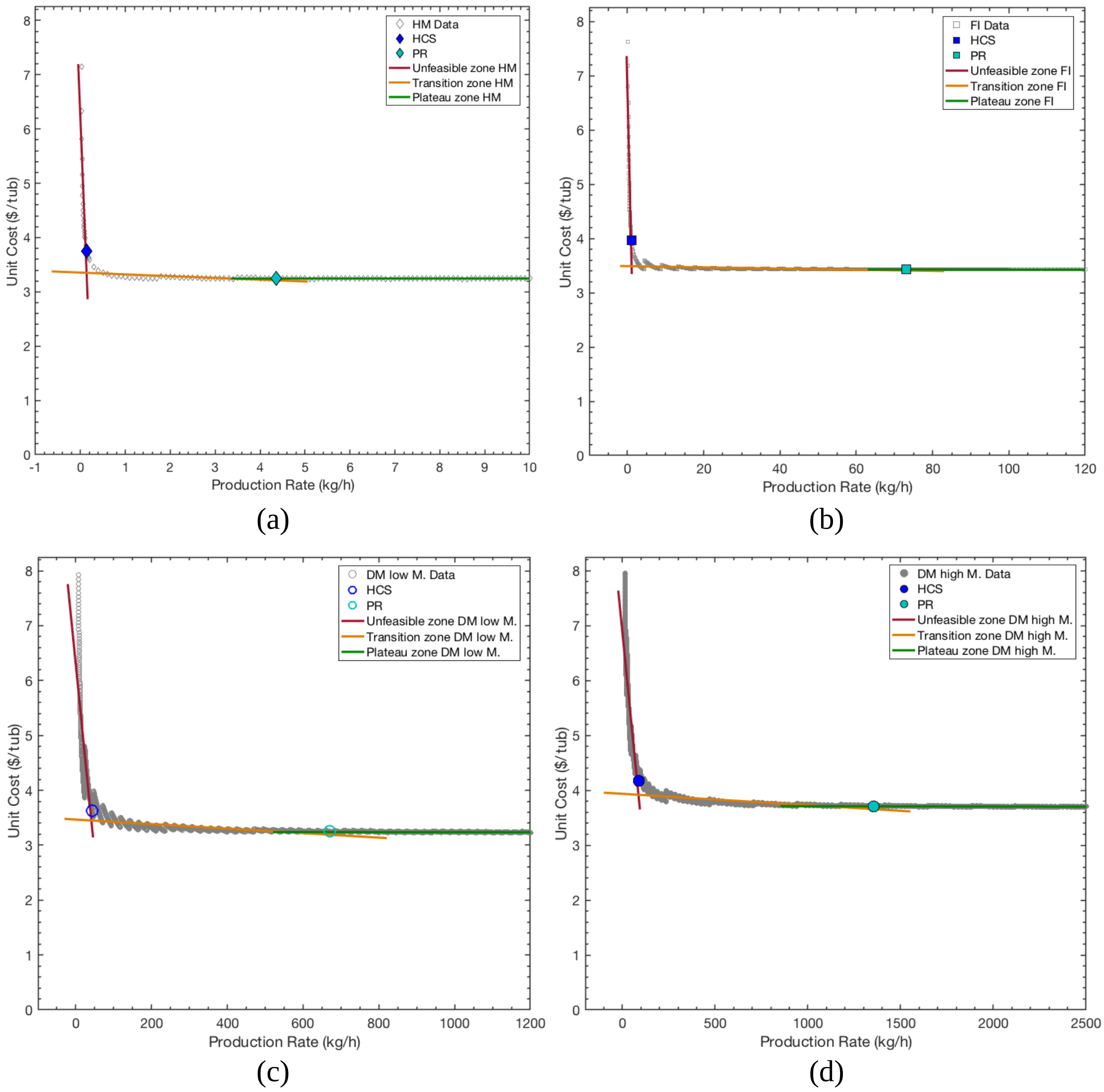
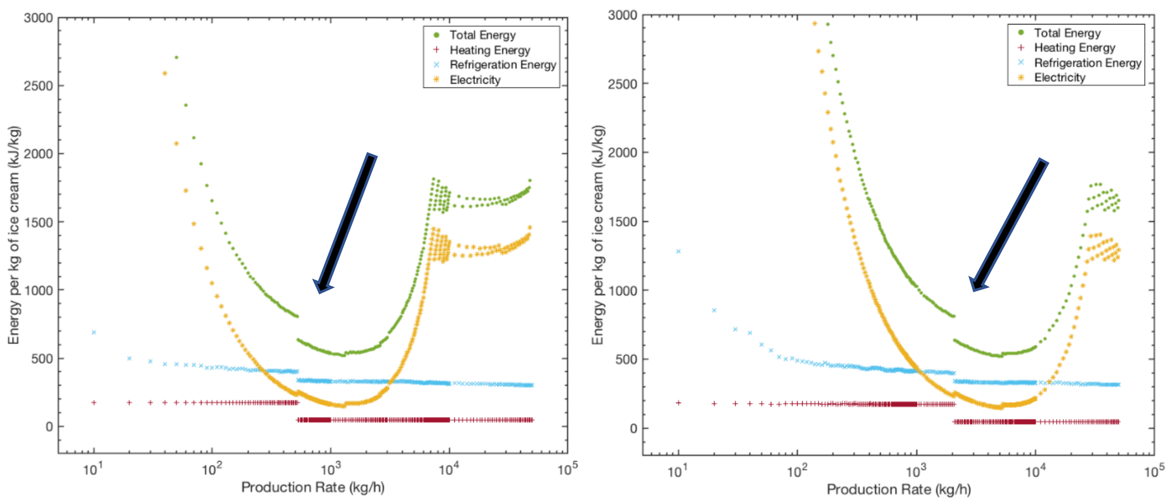


Figure 5.16. Identification of the three different operation regions defined in this work for artisan manufacturing scenarios: HM, FI and DM (franchise and corporation management models).

5.7.5. Energy consumption of industrial and artisan manufacturing processes

The energy consumption for the ice cream manufacturing has been previously studied, giving approximate values ranging between 1.90 and 3.70 MJ/kg (Cleland et al., 1981; Carlsson-Kanyama and Faist, 2000; Hendrickson, 2001). Ingredient production is significant, e.g. milk powder (16.22 MJ/kg), cream (1.18 MJ/kg) or condensed milk (4.6 MJ/kg) (Ladha-Sabur et al., 2019). Without a contribution from raw material processing, the energy directly related only to ice cream processing is ca. 0.70 MJ/kg (Foster et al., 2006; Fisher et al., 2013). Here, raw materials are purchased ready-to-use, so similar numbers to the latter are expected.



(a) (b)

Figure 5.17. Energy consumption for (a) Single plant manufacturing and (b) Four plants manufacturing. The number of four lines is randomly chosen to show the effect of splitting production in the energy demand. A discontinuity is shown when the process shifts from batch to continuous pasteurisation, which enables heat regeneration.

Electricity and natural gas are the sources involved in industrial ice cream manufacturing. Refrigeration is electricity-intensive, and the consumed energy is related to the shaft work of the two mechanical refrigeration cycles –ammonia and R404 a– used to perform the different refrigeration stages –i.e. cooling, freezing, hardening and storing. The whole electric consumption is the sum of all equipment power, including the pumping energy. Conversely, natural gas is consumed at the boiler comprising the auxiliary water cycle necessary for the heat supply at the pasteurisation.

Fig.5.17 shows the profile of the specific energy use for the premium ice cream processing in an industrial plant. The discontinuity shown in the figure is due to the change from batch pasteurisation to continuous pasteurisation. Continuous operation saves heating and cooling energy by including heat regeneration. The high energy values found at low productivity decreases as throughput increases as a result of the power consumption of that equipment operating below their maximum capacity, and the inversely proportional relation between electric consumption and storage volume. For a single plant (*Fig.5.17(a))* a global minimum is observed at 1300 kg/h, keeping the low specific energy values until capacities above 3250 kg/h are reached. Higher ice cream productions in a single line comprise higher head loss, specially at the PHE, so pumping power grows. The minimum location is displaced to higher throughputs values, as the productivity is divided in four plants and thus four production lines. A relative maximum is then achieved, stabilising the pumping energy demand when an additional channel is assumed in the PHE design and thus the head loss decreases.

On the other hand, artisan-based manufacturing scales comprise full-electric powered processes. They are designed as batch processes that use manpower to transport the product between units. The specific energy consumption is thus computed by the sum of power consumption at each piece of equipment comprising the sequential process, during the corresponding residence time. A constant specific energy consumption is found for these manufacturing scales for production capacities above 100 kg/h (see *Fig.5.18*). Lower volumes show discontinuities due to the addition of a new facility with non-full capacity units. HM proves to be the most energy effective of the artisanal scales (1150 kJ/kg), followed by FI that uses a 10% more. DM requires 1780 kJ of electricity per kg of ice cream produced, thus increasing the energy demand of the artisan process a 55%. A breakdown of the energy consumption of all scales is carried out in the next section.

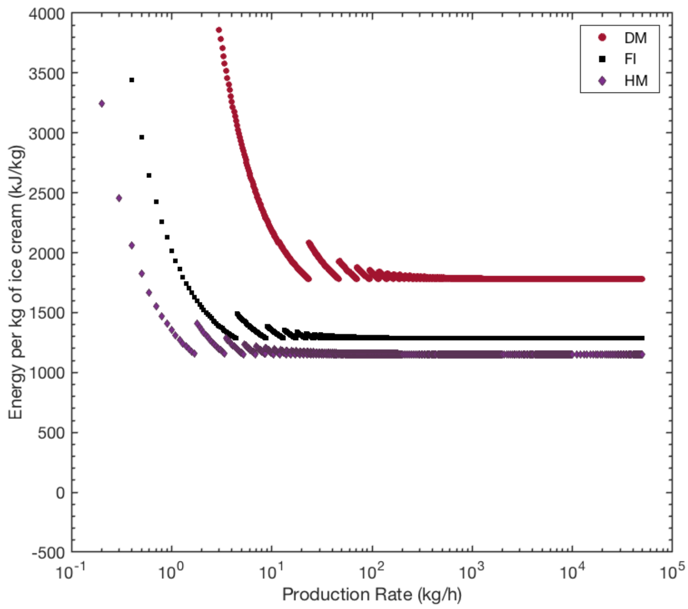


Figure 5.18. Energy consumption for HM, FI and DM. The integer constraints for processing equipment cause discontinuities in the energy plot. Minimum consumption is achieved when operating at full capacity.

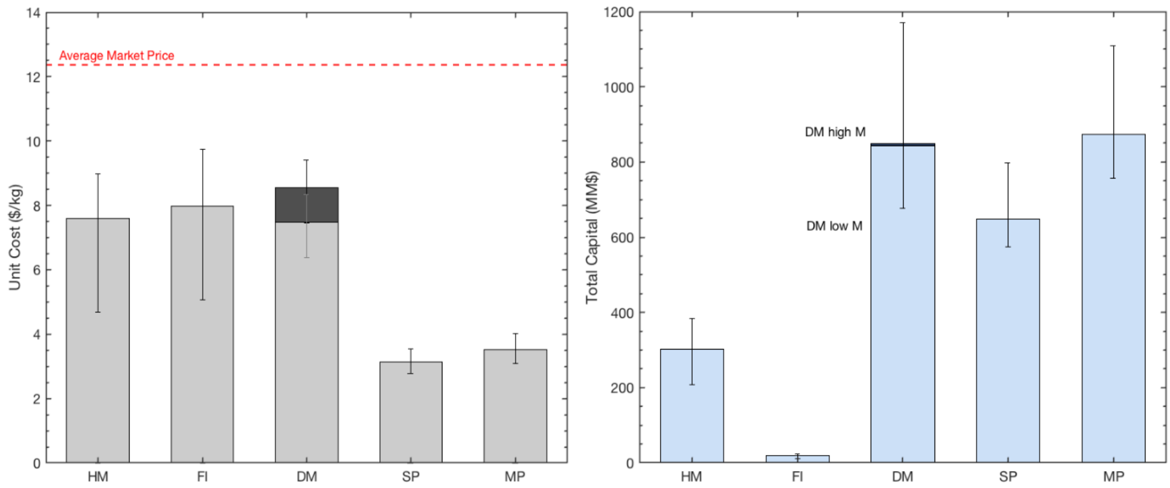
5.7.6. Case study: Fulfilling the forecast expansion of the UK ice cream demand

As a case study a scenario similar to the UK demand of ice cream is assessed here. According to 2018 data, the annual sales volume of ice cream manufactured in the UK was 328,055 m^3 (ONS, 2019). A production rate of 86,500 kg/h (considering the industrial operation mode) is enough for covering that demand. A homogenous demand is assumed here, so only premium ice cream sold in packages of 500 ml is produced.

The five different manufacturing scales –i.e. HM, FI, DM, SP and MP– are evaluated here. A UK-based framework only supplied by a HM model would comprise 49,744 scattered facilities over the country, employing an equivalent number of individuals. FI reduces this number to 19,630 facilities, due to an increase in the production per facility and worker. For DM, the catering sized scale would require 3,676 local branches to reach the required ice cream productivity. On the other hand, industrial manufacturing is represented by a theoretical single plant production scenario, and a set of plants supplying a demand similar to the one in UK. Within the multi plant scenario, the size of a single plant is set according to the results obtained in sections 5.7.4 and 5.7.5. A throughput of 3,330 kg/h is thus chosen, representing the first point of the plateau operation region with the minimum energy consumption. The resulting number of industrial plants that would satisfy the analysed scenario is 26. *Table D.4* list the design of the equipment comprising the production line, while *Table D.3* shows the mass and energy flows of the streams comprising the plant process.

5.7.6.1. Production cost

The expenditure involved in ice cream production, represented as the cost per kilogram manufactured, for the six different scenarios, is shown in *Fig.5.19*. Production in single factory is the cheapest (3.13 $/kg). MP shows a small increase of 15 % in manufacturing costs, which suggests it might be a more profitable scenario due to the transportation and storage cost saving linked to decentralisation. These have not been considered here.



(a) (b)

Figure 5.19. Analysis of all manufacturing scales in a UK demand scenario: (a) Cost per kg of ice cream (b) Total capital required. The error bars represent the trust region on the cost estimation.

Conversely, artisan manufacturing methods substantially increase costs, mainly caused by the raw material retail price. DM franchise model gives the lowest artisan outlay (7.49 $/kg), increasing by 14 % when more centralised management is assumed. HM shows similar costs (7.59 $/kg), while FI adds the rent of facilities and equipment. The great significance of raw materials in the whole cost –around 60%– gives wider uncertainty for artisanal manufacturing (error bars in *Fig.5.19*). The lower bound, assuming a deduction of the retailers' profit at the raw materials price, results in more competitive cost.

5.7.6.2. Total capital

The lowest initial investment is linked to FI method. Capital cost only considers working capital as equipment and facility are rented and the manufacturer does not own the assets used for the production. Despite in HM the equipment is assumed to be under-used existing kitchenware and no initial investment is needed, its value is included in the capital when it's manufacturer's property that eventually should be replaced for new one. For a DM net comprising catering equipment, an initial investment (842,7 MM$) similar to MP (873,7 MM$) and higher than SP scenario (649.5 MM$) is found.

5.7.6.3. Net profit

For a manufacturing scenario to be feasible, it must produce economic benefits, i.e. a positive and sufficient annual net profit. Here, the average market price is kept constant in the Net Profit calculation for all the scales. Results show an annual profit after taxes, for a single facility in each artisanal scale, of 21.9 k$/year for HM, 50.2 k$/year for FI and 298.1 k$/year for DM (franchise model), decreasing by 22.3% when high management cost are considered. Fig.5.20 shows the variation of Π_{fac} for the two selling formats of premium ice cream and the two flavours (chocolate and vanilla) of standard ice cream considered in this work, including uncertainties (represented as error bars). When premium ice cream is sold in a smaller format, i.e. 150 ml, the higher increase in selling price than in production cost results in tripling the profits. On the other hand, standard ice cream is only profitable for both flavours at FI scenario, while only vanilla flavour gives a negligible profit in DM franchise model (2.7 k$/year). Chocolate ice cream is slightly more expensive to produce than vanilla ice cream.

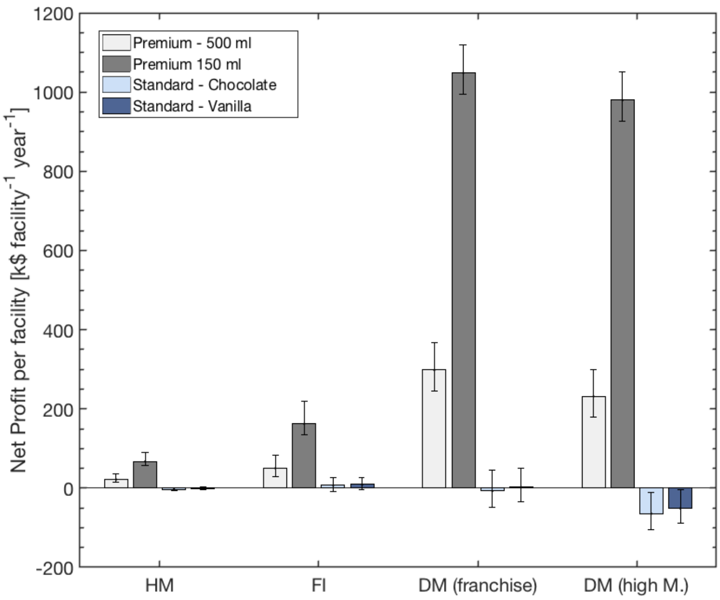
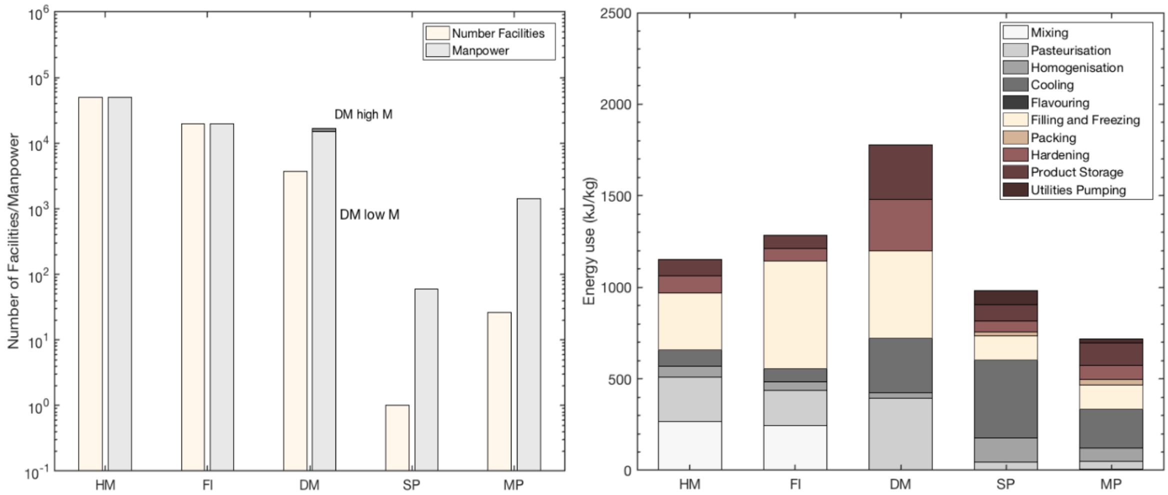


Figure 5.20. Net profit per facility for the artisan manufacturing scales. The effect of the product formulation and the selling format is plotted in this figure. The error bars represent the trust region for the given results.

Industrial manufacturing scales result the most profitable option due to the low manufacturing cost achieved. After estimating that a 21% of the retail's price is kept as supermarket benefit (Chidmi and Murova, 2011), SP profit in a UK scenario ascends to 1.4 G$, while for MP comprising 26 plants is 47.7M$ per manufacturing plant. *Fig.5.20* displays the number of facilities and labour required to supply the UK demand for each manufacturing scale. The whole net profit would be the products of these numbers and the given Π_{fac}.

5.7.6.4. *Energy use and carbon footprint for ice cream manufacturing*

A breakdown of the energy use per unit operation has been performed. *Fig.5.21* shows a bar chart comparing all the manufacturing methods.



(a) (b)

Figure 5.21. Analysis of all manufacturing scales in a UK demand scenario: (a) Number of facilities and manpower –logarithmic y-axis– (b) Total energy consumed per kg of ice cream manufactured.

In absolute numbers, a MP net of industrial plants results the lowest energy demanding scenario (0.72 MJ/kg). Despite the energy use at the product and raw materials storage increases in comparison to a large single plant manufacture, the lowest pumping energy required at the smaller production lines –mainly at cooling and homogenisation stages– causes this result. Thus, SP needs 0.98 MJ/kg of ice cream manufactured. For the artisan manufacturing methods, HM has the lowest power demand, 1.15 MJ/kg. Freezing small batches on a kitchen scale is more energy effective. The 3-in-1 freezer used in FI processing increases the power demand of the smallest artisan process to 1.28 MJ/kg (11% more). Finally, the modular process of DM is the lowest efficient manufacturing method (1.78 MJ/kg). The addition of the blast freezer for hardening, and chilling and freezing cabinets for storage increases the power demand. Mixing is performed in the pasteuriser while heating the mix, so the energy use at this stage is included in pasteurisation.

When assessing the GHG emissions associated to the previous energy demand data, MP reach the lowest value with an estimated specific carbon footprint of 0.080 $kgCO_2e\ kg^{-1}$. The rest of the scales are sorted in an increasing environmental impact as follows: SP (0.110 $kgCO_2e\ kg^{-1}$), HM (0.132 $kgCO_2e\ kg^{-1}$), FI (0.147 $kgCO_2e\ kg^{-1}$), and DM (0.204 $kgCO_2e\ kg^{-1}$).

5.8. Conclusion

To evaluate decentralisation in the ice cream manufacturing, a model-based tool is developed here. Five different manufacturing scenarios, characterised by a different degree of decentralisation, have been designed. Scenarios from a single high-volume processing plant to domestic kitchen production, SP, MP, DM (franchised and high management models), FI and HM have been compared and assessed in both economic and environmental terms. The tool shows flexibility in allowing different product formulations to be examined. The thermophysical properties and rheology of standard and premium ice cream have been modelled. In addition, different package sizes are considered to develop a sensitivity analysis on the process profitability. Uncertainties are also accounted to provide trust regions for the given results.

The throughput range of application for each manufacturing scale is identified. Unfeasible, transition and plateau zones are identified following Section 5.7.4. HM is the most profitable scenario for productions below 45 kg/h. FI shows a similar operation range but with higher production cost. DM is the preferred option within 45-650 kg/h interval when franchise management is assumed, while SP (assuming one line per plant) is the desirable manufacturing scale at higher production rates. The optimal operation for a single processing line is found at 3325 kg/h, so an additional plant (or line) is advisable when this capacity is reached.

A case study assuming an ice cream demand similar to the one in UK has been performed. SP shows the lowest cost. A MP scenario –comprising 26 plants– has a better energy efficiency, lesser environmental impact and higher social impact that might make this method preferable over SP. The slightly higher manufacturing cost (15 %) and a bearable increase on capital cost (35 %) for MP can be easily balanced with economic savings in distribution in the following supply chain stages. Artisan manufacturing scales cannot compete in cost with industrial processing, mainly due to the increased retail price of raw materials. However, the profitability of the small-scale business may be sufficient to attract freelancers and entrepreneurs –e.g. 21.9 k$ facility^{-1} year^{-1} after taxes for HM. The profitability is increased when premium ice cream is sold in small packages for all scales, while only industrial manufacturing can provide substantial benefits for standard ice cream, assuming the current market price. Job creation is found as a positive social factor assigned to decentralised manufacturing scenarios. HM, FI and DM respectively requires 49,750, 19,650 and 15,000 (16,500 for high management) workers, thus outnumbering by far the employments linked to industrial manufacturing –60 for SP and 1,410 for MP.

Regarding the energy used, MP was the most energy efficient (0.72 MJ/kg), while DM shows the highest energy use (1.78 MJ/kg). This difference is higher in the environmental impact, as artisan processes are fully electric based, with 0.080 and 0.204 $kgCO_2e\ kg^{-1}$ respectively. Within artisan manufacturing, HM has the lowest energy use (1.15 MJ/kg) and environmental impact (0.132 $kgCO_2e\ kg^{-1}$), not too far from the industrial one and making worth to study the impact of the whole supply chain, looking for big shavings in transportation and storage caused from decentralisation for a highly refrigerated product.

Overall, in addition to the evaluation carried in this work, the developed tool has demonstrated to have a potential use to help a company to determine the best manufacturing scale option for a defined market opportunity and with a specific available capital.

Chapter 6

Comparison between the three products

6.1. Introduction

Comparison between the three food products evaluated in previous chapters, i.e. cereal porridge for baby feeding, sliced bread and ice cream, is performed here. First, cost correlations have been obtained to represent the production cost and total capital linked to each manufacturing method, namely Home manufacturing (HM), Food incubator (FI), Distributed Manufacturing (DM), Single industrial plant (SP) and Multiple industrial plant (MP). Next, the behaviour of the characteristic points that define the operability of each scale, i.e. *High change on slope* (HCS) and *Plateau reaching* (PR), with respect to variations on both production scale and food manufactured, is studied. Finally, total capital invested, net profit per site, energy use and carbon footprint are contrasted to complete a multiple-product evaluation of the economic performance and environmental impact for all the manufacturing scales, in a UK demand framework.

6.2. Cost correlations for unit cost and total capital

A regression study was performed to establish correlations between production rate and cost for all the manufacturing methods. Least-squares methodology is used for this purpose. A two-term power fit (Eq.6.1) is chosen as the best approach for unit cost (C'_{prod}) data. The addition of parameter c to a power regression might initially seem to have no physical sense, as it represents the intercept on the x-axis while the models show an asymptotic behaviour when production tends to a zero-value. It minimises, however, the existing residuals –when compared to a single-term power model fit– even at very small production rates. A linear model (Eq.6.2) is selected for capital cost (I). To force the intercept of the model to equal zero –i.e. no investment for no production– damages the goodness of fit, especially at small productivities, so parameter e is therefore considered.

$$C'_{prod}(\$/\text{kg}) = a \times q\ (kg/h)^b + c \qquad \text{Eq.6.1}$$

$$I\ (\text{M\$}) = d \times q\ (kg/h) + e \qquad \text{Eq.6.2}$$

Table 6.1. Unit cost and Total Capital fit parameters for all the manufacturing scales when processing cereal porridge, sliced bread and ice cream.

	Unit Cost [$ kg^{-1}] *–Eq.6.1–*			Total Capital [M$] *–Eq.6.2–*	
	a	b	c	$d \times 10^3$	e
Cereal Porridge					
HM	0.070	-1.030	6.132	1.972	$9.653 \cdot 10^{-4}$
FI	0.930	-1.190	6.857	0.515	$5.527 \cdot 10^{-5}$
DM -franchise-	58.67	-1.038	7.441	2.656	0.0136
DM -corporation-	130.80	-1.022	8.666	2.748	0.0177
SP	936.9	-0.974	3.421	10.080	7.656
2P	1,602.0	-0.971	3.413	9.919	15.660
Sliced Bread					
HM	0.021	-1.050	1.035	8.804	$6.392 \cdot 10^{-3}$
FI	0.719	-1.152	1.362	0.216	$6.714 \cdot 10^{-5}$
DM -franchise-	56.43	-1.150	1.454	1.848	0.0409
DM -corporation-	95.29	-1.104	1.701	1.887	0.0451
SP	818.9	-0.998	0.769	5.167	10.530
2P	1,619.0	-0.998	0.844	5.729	11.890
Ice cream					
HM	0.166	-1.021	7.588	3.491	$1.161 \cdot 10^{-3}$
FI	1.752	-1.008	7.956	0.219	$0.257 \cdot 10^{-4}$
DM -franchise-	87.64	-1.003	7.259	9.741	0.116
DM -corporation-	174.40	-1.001	8.239	9.800	0.120
SP	1163.0	-0.981	3.197	7.732	7.420
2P	1871.0	-0.963	3.138	7.964	12.670

Table 6.1 lists the fitting parameters for the three foods manufactured using any of the six production scales characterised. Multi-plant scale is represented by only one scenario, i.e. production in two plants (2P). All the regressions have achieved a R^2 parameter above 0.997 without any robustness implementation, which shows a great prediction capacity.

6.3. Characteristic points (HCS and PR) and operational regions

In prior chapters, unit cost curves were obtained for each manufacturing scale along a wide range of throughputs. Two characteristic points –i.e. HCS and PR– were found to divide the production into three operational regions, namely *Unfeasible*, *Transition* and *Plateau*. Unfeasible zone comprises the range of throughput where operation is not recommended, as cost is very sensible to changes in productivity with small capital variations. Transition region operations can achieve cost savings by increasing throughput but at the expense of significantly greater capital injections, while plateau region scenarios have reached the maximum cost efficiency from economy of scale, and higher production rates do not achieve perceptible cost reductions. HCS and PR are characterized by three parameters: size of facility (kg/h), production rate (kg/h) and unit cost ($/kg). A 3D plot is developed to examine the trade-offs between manufacturing scale and feasibility of production. *Fig.6.1* comprises six graphs corresponding to both HCS and PR representation for the three food items evaluated. The two-dimension projections – i.e. *i*) Throughput–size of facility, ii) Throughput–unit cost and iii) size of facility–unit cost – are plotted for a better analysis of their behaviour.

In general, bigger facilities require greater throughputs to reach feasible production conditions (HCS point). Projection *i*) shows a similar trend for the three food items. Higher productions rates are required for bread to reach HCS due to the higher fixed cost/variable cost ratio involved, e.g. DM point for bread manufacture is one order of magnitude above ice cream and cereal porridge production. This fact is also supported by the steepest growth in throughput found when production is divided from SP to two plants in bread manufacturing (see *Fig.6.1.c*). Higher unit costs are associated, however, to those HCS points corresponding to cereal porridge and ice cream. Greater investment –and hence fixed cost– for cereal porridge facilities, and more expensive raw materials –variable cost– for ice cream, are the main causes for the increase of expensiveness when compared to bread.

Trend lines represented in projection ii) are different for each product. The greater drop in cost for a feasible industrial production with respect to artisanal methods is found for ice cream (see *Fig.6.1.e*). Splitting ice cream production in two plants does not involve a wide rise in cost, while for cereal porridge that change is significant. Cereal porridge manufacturing in 2P reaches the transition section at similar production rates than SP, which causes the big jump shown in *Fig.6.1.a*. In the case of sliced bread, feasible operation is reached at similar unit cost for all the scales, except for HM that can perform at lower costs. Projection iii) shows that for HCS points, the higher impact of management cost assumptions for DM is found for cereal porridge. The smaller size of a DM single facility producing porridge, when compared to the other two food products, enhances the effect of management cost. Points corresponding to SP and 2P are located at smaller size facilities, which is consistent to the fact that HCS points are found at lower throughputs for this product.

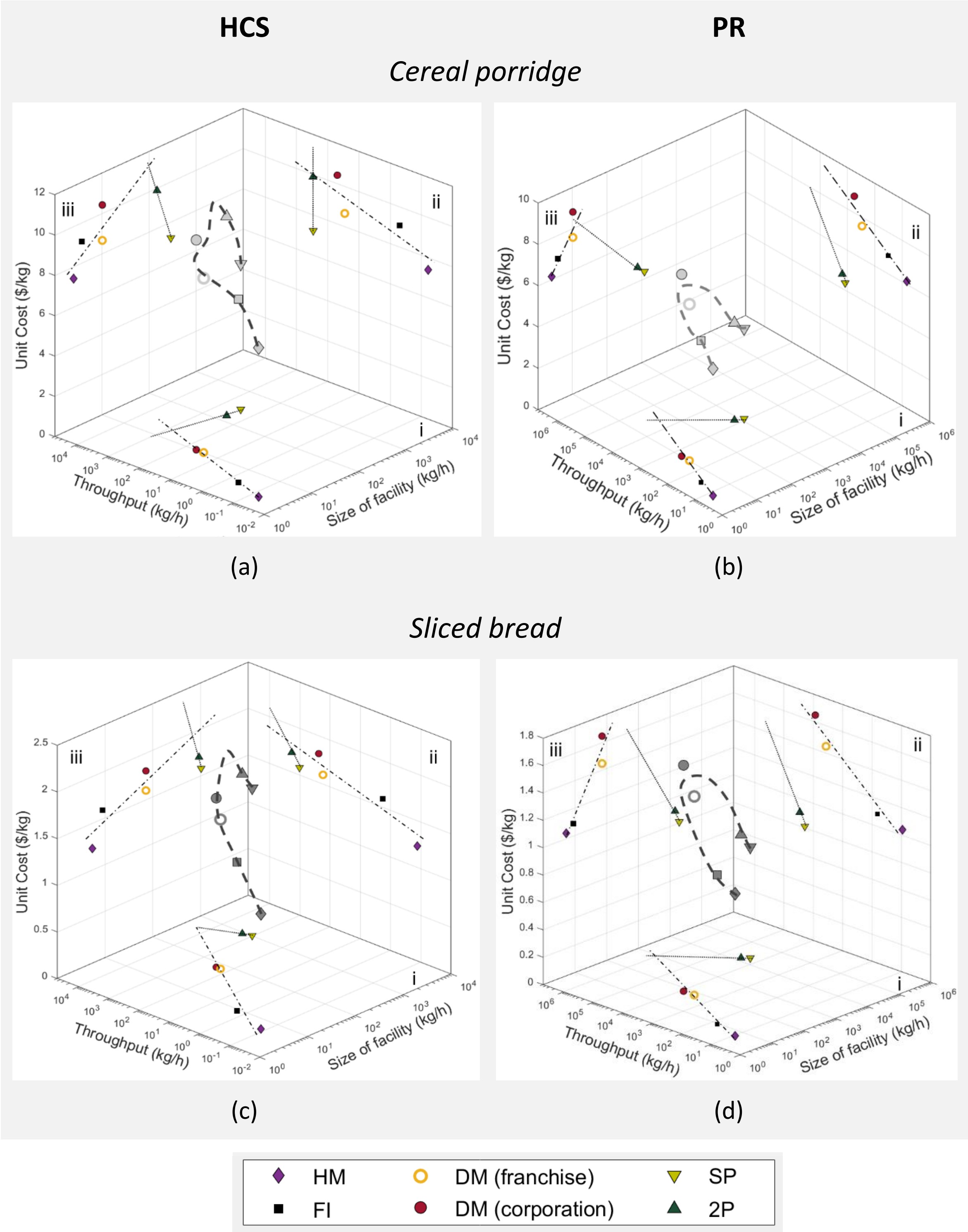


Figure. 6.1. Characteristic points of production cost curves for all the scales. Graphs on the left represent *high change on slope* (HCS) points, while graphs on the right represents *plateau reaching* (PR) points for each manufacturing scale. The 3D graph represents the evolution of those points as a function of Throughput, Size of facility and Unit cost. Linear trend lines are shown: dotted for *industrial* and dot-dash for *artisan* methods. Cereal porridge (a,b) and sliced bread (c,d).

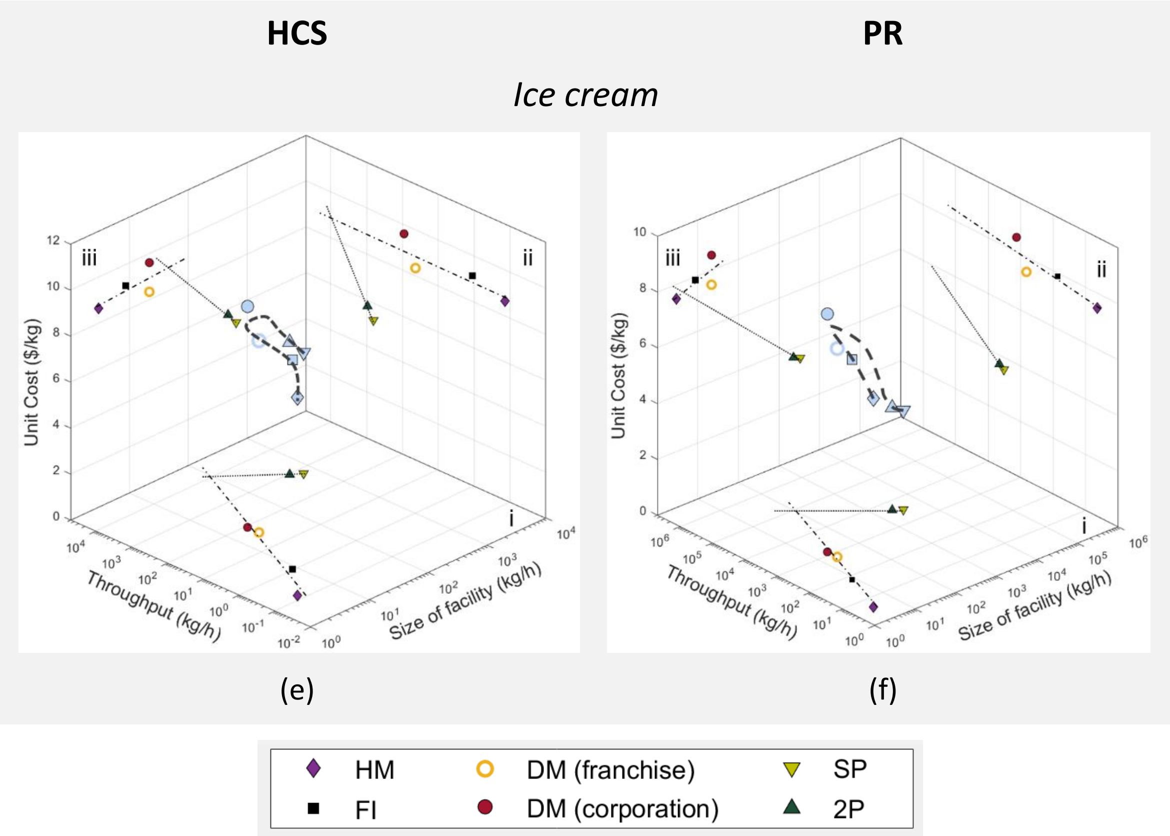


Figure. 6.1. *(cont.)* Ice cream (e,f).

The approximate production rate at which economy of scale stops improving cost efficiency by increasing production for each manufacturing method, i.e. PR points, are also compared. The behaviour is very similar to HCS points, so PR points seem to be affected by the same factors. Projection i) shows a similar behaviour for the three food items assessed with respect to the manufacturing scale: bigger facility size needs higher throughputs to reach the plateau.

HM and FI have PR points located at production rates of the same order of magnitude for all products, i.e. 10^0 and 10^1 respectively. Greater differences are found for DM and industrial manufacturing methods. Cereal porridge is the item that achieves their maximum efficiency faster, followed by ice cream. Bread requires throughputs of one order of magnitude higher –10^3 for DM and 10^4 for SP and 2P– than the other two foods (see *Fig.6.1.d*), and thus transition regions, i.e. throughput range between HCS and PR, are wider for bread. Projections ii) and iii) for porridge and bread are comparable. Unit cost at which PR is achieved increases with facility size for artisan manufacturing scales, while for industrial production the cost is much lower and decreases with the number of plants involved. The smallest scales (HM and FI) can reach cost close to SP and 2P for these two foods. For ice cream, however, all artisan scales achieve their maximum cost effectiveness at similar prices, while industrial manufacturing scales greatly minimise cost in a similar way than HCS points (see *Fig.6.1.f*).

6.4. Economic and environmental impact assessment

The parameters that characterise each manufacturing scale for a food in economic and environmental terms, individually evaluated in previous chapters, are compared in this section. Thus, total capital, net profit, energy use and carbon footprint are defined as intensive properties and compared. Production cost is omitted here as no relevant information can be extracted from this parameter in a multi-product assessment, further than the relative cost of one product with respect to the others (already discussed in Section 6.3). The data obtained for a UK framework is used in this comparison. All the defined manufacturing scales will be included. Multi-plant scenarios comprise here those plant sizes that represent a certain advantage over the production in a big single plant. For cereal porridge, MP consist of three plants that reduces the double drum drier size to model #2 from the corresponding catalogue (SP needs model #4 as resulted from Chapter 3). In bread production, six plants are considered so each site comprises only one tunnel oven, and therefore one processing line per plant. For ice cream, twenty-six plants with an improved energy efficiency (as discussed in Chapter 5) satisfy the UK demand for this item.

6.4.1. Total capital per unit of production rate

Figure 6.2 compares the efficiency of the invested capital, defined as the total capital used per unit of production rate, for the manufacturing of each food at any production scale. A more efficient use of capital cost would result in less investment for a similar productiveness. Uncertainties are accounted to provide a trusted region in the results.

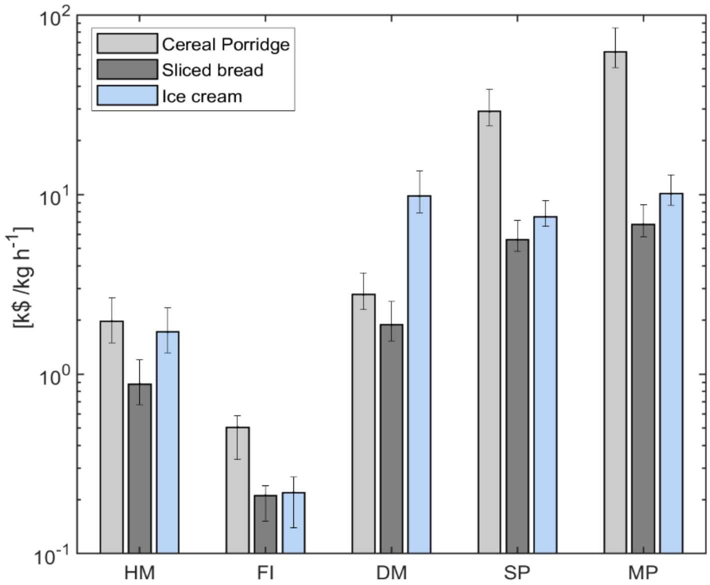


Figure. 6.2. Total capital per unit of throughput. The five manufacturing scales are applied and compared for the three food products evaluated in a UK demand alike scenario. Logarithmic scale is chosen for the y-axis for a better reading of the results, while error bars represent the confidence region of the given results. Cereal porridge has lower capital efficiency in production for all scales, except for DM, where ice cream requires a higher investment per kg/h produced. Bread has the lowest capital cost in all the production method.

FI is the scale involving less investment for the three food products with values under 1,000 $ per kg/h of product manufactured. The total capital only comprises inventory cost, so it is directly related to the price of raw materials and the stock size. Bread involves the cheapest ingredients and therefore shows the lowest value. Conversely, cereal porridge manufacturing uses higher priced materials and has the highest investment for FI. Despite that ice cream ingredients are more expensive, the amount of product comprising the inventory is smaller. Cereal porridge and bread models assumed similar inventory sizes corresponding to one week of production, as the only limitation is the storage room capacity. However, ice cream needs to be preserved below -15˚C. The resulting FI inventory is two-days of production, which corresponds to the freezing equipment capacity where ice cream is stored. This smaller inventory size makes the total capital value for ice cream to remain below the one for cereal porridge at FI production.

Total capital involves the purchase of instrumentation for the rest of manufacturing scales in *Fig.6.2*. When comparing the results obtained in Chapters 3,4 and 5, it turns out at ice cream production uses the most expensive equipment. This fact makes the gap between porridge and ice cream to narrow for HM (see *Fig.6.2*). The impact is greater in DM, where catering equipment for ice cream production is seven times more expensive than bread or porridge instrumentation. Cereal porridge involves the highest investment per kg/h of product manufactured at industrial scales. The greater working capital, more expensive machinery and larger plant size (higher land and building cost) with respect to throughput, makes the capital efficiency lower for porridge. For ice cream, ingredients are still expensive, so the working capital value is similar to the porridge one. However, the industrial equipment is cheaper with respect to production rate and achieve an improved capital cost efficiency than DM for the same product (singular case). Bread production comprises the lowest investment for all the manufacturing scales, including industrial production. All cost items that comprise total capital are similar to ice cream counterparts. However, the cheaper production cost allows a lower working capital so an improved efficiency with respect to ice cream is achieved.

6.4.2. Net profit per facility

The food product that shows highest profitability when it is produced using decentralised manufacturing scenarios is identified. The net profit per facility for all artisan methods is compared for this purpose. Industrial manufacturing achieves much greater values due to the lower costs and the small number of facilities involved in the production. Results for SP and MP scenarios are not assessed in this section, but can be found in the previous chapters (sections *3.5.4.3* for porridge, *4.5.4.3* for bread and *5.8.6.3* for ice cream.

Ice cream is a value-added product that greatly enhances its value after processing. *Fig.6.3.* shows how ice cream always provides the higher profits. Cereal porridge also achieves feasible profits for all the scales. HM and FI, that comprise freelance worker scenarios, exceed the national minimum wage for the UK (ca. 16,000 £/year), while DM sites improve the income at any management organisation considered. On the other hand, bread is the food item with the lowest value added from processing, and thus gets less advantages from decentralised production. Very poor profits are achieved for HM and FI, while for DM, assuming the corporation management model give economical losses. This situation suggests that these scales must increase the selling price over the industrial bread one. The only feasible production method for bread is DM using franchise model, so that management costs are minimised. Uncertainties in bread are strongly influenced by raw material prices. Potential discounts in material costs (e.g. cooperative purchasing) can greatly improve profitability of bread production. DM is the scale that show the most recognisable variations, where the corporation model could become profitable and franchise model might surpass cereal porridge benefits.

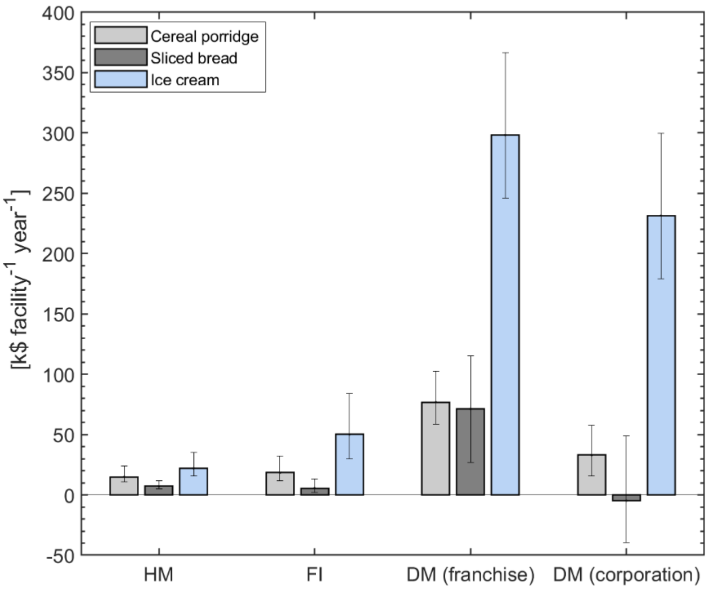


Figure. 6.3. Net profit per facility comparison of artisan scales profitability for the three food products evaluated in a UK demand scenario. Error bars represent the confidence region of the given results. Ice cream proves to be a value-added product resulting in the highest profits. Cereal porridge achieves feasible profitability for all the scales assessed, while bread making can only compete at industrial prices using a DM scenario with a franchise management model.

6.4.3. Energy use and carbon footprint

The environmental impact of manufacturing is evaluated by estimating the carbon emissions associated with production. First, the energy consumption for each process is assessed. In cereal porridge and bread manufacturing, two alternative energies are considered to check the effect of different power sources on the studied parameters. Electric and gas ovens are available in the market for artisanal production, while industrial processes can variate the type of boiler used for steam production. Biomass –i.e. the lowest carbon emissions– and natural gas –widely used fuel that is also a choice in artisanal processes– are the two energy sources included in the comparison. The ice cream manufacturing process, however, is more rigid. Electricity is used for refrigeration in all scales and no alternative energy sources can be compared.

Fig.6.4 plots the energy demand results, obtained from the modelling tool, for each scale and food item produced. Ice cream is the product with the lowest energy use. Mechanical refrigeration involves less energy than thermal processes. Conversely, cereal porridge shows the highest values. A larger amount of water needs to be evaporated for this item, that reduces its water content from 80 w%, reached in gelatinisation, to a 6 w% as the final product features. Bread making demands less energy, e.g. artisan processes use one fourth of the porridge values. The dehydration of the product is much lower, from 37% to 25%, which reduces the energy use. When the same power source is assumed, industrial processing results more energy effective for the three foods –see natural gas data for porridge and bread or ice cream case in *Fig.6.4*. The porridge process has the higher drop in efficiency when the production is divided in smaller plants (as later assessed in this section). This effect is not significant for bread manufacturing, while in ice cream production, the energy demand is reduced when the processing line is optimised in a MP scenario.

In previous chapters, it was indicated how the efficiency of the equipment is different depending on the energy supplied. Electric domestic equipment consumes less energy per kg of product manufactured than a fossil fuel option, and biomass boilers shows the lowest efficiency in industrial processing. The interest on alternative sources, however, might be related to a possible advantageous environmental impact. *Fig.6.5* shows the greenhouse gas emissions related to the scenarios plotted in *Fig.6.4.* Porridge and bread results indicate that electric choices have the highest carbon footprint. The environmental impact of artisanal processes can be reduced approximately a 30 % when natural gas is selected for both products. For ice cream, the smallest scales (HM and FI) carry the lowest emissions. Conversely, despite DM encompass less specific energy for ice cream processing than bread using gas rack ovens, the higher electricity share of the former leads to a greater environmental impact for this scale.

Industrial processes are also evaluated here. Cereal porridge is the product that involves the highest emissions due to the larger amount of energy consumed. When biomass is used to feed the steam boiler, the environmental impact of manufacturing is minimised due to its significantly smaller greenhouse gas conversion factors. The emissions decline on steam generation is so important that porridge–bread impact is reversed (see SP scale in *Fig.6.5*). Despite having a much greater energy demand, cereal porridge major energy consumption is related to steam generation (ca. 85%) and when the carbon footprint of that stage is minimised when biomass is selected to feed the boiler, the environmental impact of the whole process drops below bread making outcome. However, when production is divided in smaller plants, the resulting loss in energy use efficiency for porridge processing is caused by an increase in electricity consumption due to the extra machinery needed. The carbon emissions thus are boosted, and the MP scenario for cereal porridge results in a higher environmental impact than sliced bread. For ice cream production, carbon footprint data is consistent with energy demand results. The superior emissions associated to an SP scenario, with values similar to industrial bread making, are reduced when the production is split using MP method, which results as the most environmentally friendly manufacturing scenario from all the ones compared here.

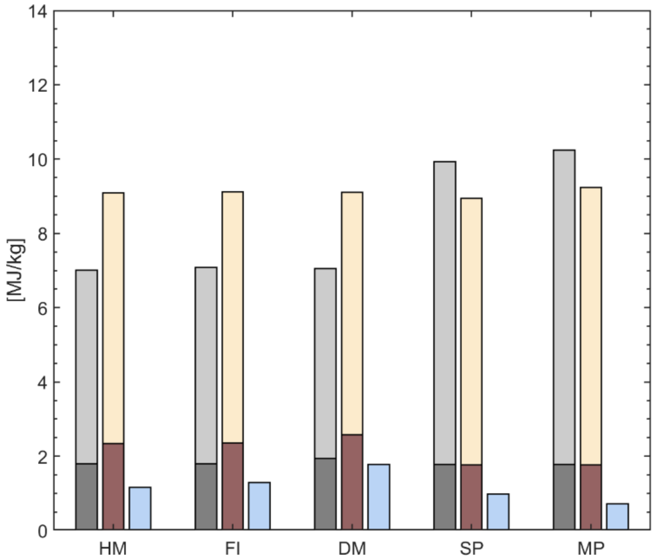


Figure. 6.4. Three foods energy use comparison. Ice cream needs less energy per kg of product manufactured. Cereal porridge and bread both involve thermal heating and have superior energy demand, with the former showing higher values due to the large water evaporation involved. Natural gas (artisanal) and biomass boiler (industrial) lower the energy efficiency of the processes.

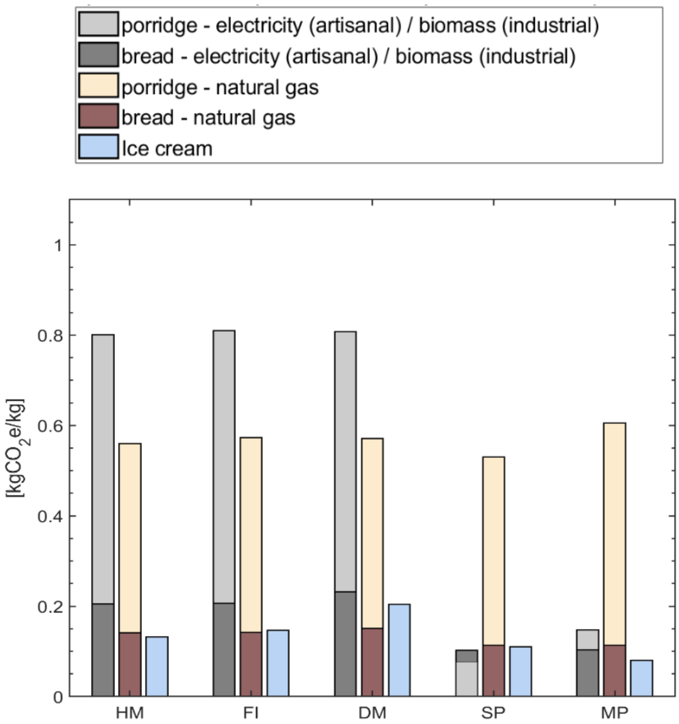


Figure. 6.5. Three foods carbon footprint comparison. Bread and ice cream processes show similar emissions at processing. Cereal porridge has the highest environmental impact due to the large energy consumption, most it used for steam production. The use of a biomass boiler minimises that impact.

6.5. Conclusion

Cereal porridge, sliced bread and ice cream processing using the five manufacturing scales, previously defined in the preceding chapters, has been compared. The regression study performed to find correlations between production cost–throughput and total capital–throughput found that the former follows a two-term power fit, while a linear regression fits the latter. Both models have a R^2 value above 0.997 for all the manufacturing scales.

The analysis of HCS and PR points showed that bigger facilities require greater throughputs to reach a feasible production and their maximum economic efficiency. The higher fixed cost/variable cost ratio in bread processing implies that bread scales need production rates above porridge and ice cream to achieve those features. Bread is the cheapest product to manufacture due to the low-cost raw materials and processing cost involved. Ice cream is the food that reduced their cost the most when it is industrially produced, while HM and FI production for bread and porridge can achieve comparable cost to industrial production when cost plateau is reached. The higher impact of management cost in DM is found for cereal porridge due to the smaller productivity of a single facility.

An economic and environmental impact study is conducted. The invested capital efficiency in production is firstly evaluated. Bread is the item requiring less investment per kg/h of production for all the scales. Conversely, cereal porridge manufacturing involves more capital cost at any scale except for DM, where the investment needed for ice cream production widely outstrip the other two foods. With respect to production profitability, ice cream is identified as a high value-added product that achieves the greater profits, while cereal porridge production return worthy incomes for all artisan scales. Bread, conversely, only shows a feasible production for DM-franchise model, while HM and FI do not reach the national minimum wage and corporation model for DM gives losses. Thus, bread selling price must be raised or any method involving discounts in materials (e.g. cooperative purchasing) needs to be implemented. Finally, energy use and carbon footprint are analysed. Mechanical refrigeration involves less energy consumption than thermal processes, which leads ice cream to be the item with the lowest energy demand. The much higher water content reduction in manufacturing leads porridge to achieve the higher values. In general, industrial processing involve lower energy consumption and emissions. Alternative power sources have been also analysed. Fossil fuels show a lower efficiency when compared to electric equipment. However, results show that the carbon footprint is minimised (30% lower) when natural gas ovens are chosen for artisanal production of bread and porridge. The electricity share is determinant on the carbon footprint of the process, e.g. for DM bread has a higher energy use but it shows lower carbon emissions than ice cream. In cereal porridge industrial manufacturing, the greatest energy is consumed for steam generation, so the use of a biomass boiler minimises carbon footprint outcome to values below bread and ice cream making for SP. An increase of electricity share in the porridge MP scenario reverses this trend, where ice cream processing involves the lowest emissions.

Chapter 7

Conclusion and future work suggestions

7.1. Overview of methodology

This research has first set a background to the existing shift in manufacturing paradigm in the search to meet the new market needs, i.e. to provide individualised and authentic products in a short delivery time to satisfy customer desires, while using improved sustainable manufacturing methods that minimise the environmental impact and involve ethical actions. The current predominant manufacturing method, based in centralisation to reduce production cost in exchange of flexible production and distribution, is challenged through engineering calculations. Many theoretical approaches propose distributed manufacturing, which involve small (and micro) scale production and localisation as an alternative model to satisfy a market increasingly dominated by consumer desires, sustainability and a preference for natural products. Up-to-date technologies –e.g. ICT, digitalisation and modern small-scale machinery– may enable artisan production methods that were discarded time ago due to their high cost and long production time. These studies inspired the development of a modelling platform that can design and simulate several manufacturing scenarios with different degree of decentralisation, i.e. from decentralised manufacturing (Home-manufacturing, Food Incubator, Distributed Manufacturing) to centralised manufacturing (Single Plant and Multiple Plant production).

The developed methodology is based on the following steps: i) Product formulation, ii) Processes flowsheeting, iii) Cost estimation and iv) Energy use and carbon footprint calculation. Production rate is firstly set as an independent variable to assess the behaviour of economic, social and environmental parameters for a wide range of throughputs. The productivities at which each scale is more cost efficient are found. The generated data is also analysed and three operational regions, with respect to operation feasibility, have been identified for each manufacturing scale: *Unfeasible*, *Transition* and *Plateau.* Finally, the modelling tool is applied in a UK framework to check the performance of the alternative production methods in a realistic scenario.

7.2. Principal findings

Three foods have been studied. The processing of a dry food item has been firstly evaluated. Dry cereal porridge has been chosen to represent the food category that might get the lowest advantages from decentralised manufacturing, due to its long shelf life and cheap storage and transportation. Results showed that the lower fixed cost comprising small scale manufacturing methods allow feasible production at very small manufacturing scales. Niche markets could be therefore satisfied with the use of this production processes. Single plant production is the preferred method for larger productions than 400 kg/h. In a UK framework, the most decentralised methods (HM and FI) can compete in cost with industrial production, while DM needs low-cost management to not raise operating cost. The barriers involved in centralised production methods are overcome by a greatly reduction of investment –e.g. DM involve a 10% of SP capital– and the use of common equipment (kitchen instrumentation). Also, manpower is inversely proportional to facility size, so employment might be created from decentralisation. Artisanal-based methods, however, resulted in a lower energy efficiency and higher carbon footprint (ca. 15% when gas ovens are used) than industrial processing.

Sliced bread making is chosen as the second case study. Bread is a fast-moving and semi-perishable food, with low value-added and a short shelf life. Decentralised production could therefore reduce delivery time and prevent the inclusion of additives on bread recipe that industrial manufacturing use to overcome the economic losses caused by bread stalling during storage. Industrial manufacturing resulted the cheapest method for production rates exceeding 3,100 kg/h. HM is the only artisanal scale that can produce bread at low prices. The low variable cost for this food –raw materials are cheap– increase the impact of fixed cost that worsens the economic efficiency of FI and DM scales. The same trend in capital and labour identified for cereal porridge is obtained here: shavings in capital and increasing manpower are achieved by artisanal production methods. For a scenario where a demand similar to the UK sandwich bread consumption is assessed, industrial processing (up to three plants) involve the lowest production cost. HM can compete in cost with industrial manufacturing, but the low value-added of bread avoid this scale to achieve worthy profits selling bread at the same price (the national minimum salary is not reached for a single facility). Artisanal methods must therefore raise selling price for a feasible bread making. With regard to energy consumption and carbon footprint, industrial manufacturing has the lowest values. However, the difference with artisanal production is not so wide (SP emissions are a 25% lower than HM) so it suggests that savings might be found when the entire supply chain is considered.

The third food item evaluated is ice cream, a semi-solid frozen food with high energy use and emissions in transportation and storage. The best advantages from shifting production to a decentralised model are expected for this item. The modelling of industrial ice cream processing has not previously been studied in the literature. Different product formulations, i.e. standard and premium ice cream, and selling formats are included in the model to check the effect of product formulation and packaging on the technoeconomic analysis. Results have shown that HM has the best economic efficiency for throughputs below 45 kg/h, when DM (comprising modular processing lines) becomes the preferred method. Industrial processing in a SP it desirable for bigger productions than 650 kg/h and, when 3320 kg/h is reached, a second processing line is advisable. For the UK case study, SP has the lowest cost, followed by a MP scenario –comprising 26 plants– that shows a better energy efficiency, lesser environmental impact and higher social impact. Artisan manufacturing scales cannot compete in cost, but profitability may be sufficient to attract freelances and entrepreneurs. HM and FI also comprise low capital cost, unlike DM that needs an initial investment similar to a single industrial plant. In an energy demand context, MP is the most efficient manufacturing scale (0.72 MJ/kg) with the lowest emissions (0.080 $kgCO_2e\ kg^{-1}$). HM is not very far (1.15 MJ/kg and 0.132 $kgCO_2e\ kg^{-1}$), while DM increase both parameters being the less efficient artisanal method (1.78 MJ/kg and 0.204 $kgCO_2e\ kg^{-1}$).

The three food items that were individually evaluated have been compared. A general trend is found showing that throughput is directly proportional to facility size to reach both feasible production and maximum economic efficiency. Bread making needs greater production rates than porridge and ice cream to achieve those objectives. The best capital cost efficiency is found for bread for all scales, while cereal porridge requires the highest investment per kg/h of production except for DM (ice cream exceed porridge values). Ice cream is the most value-added food and shows the highest profits with respect to the other two foods. Porridge artisanal manufacturing is profitable, while bread needs to raise selling prices or find raw material cost discounts (for example by cooperative purchasing) for a feasible artisanal production. In terms of energy consumption and carbon footprint, industrial manufacturing methods always show the lowest rates. Ice cream manufacturing –involving mechanical refrigeration– is the most energy efficient product. Cereal porridge and bread production comprise thermal processes that require great energy supply directly proportional to water removal. Thus, porridge needs more energy and causes the highest carbon emissions per kg of product manufactured. The study of alternative power sources shows how the electric share of the process has the highest impact on the emissions associated to the manufacture. The use of fossil fuel equipment, despite they present a decline in energy efficiency, minimise carbon emission with respect to electric choices in artisanal production. To include biomass boilers in industrial processes also deplete their environmental impact, especially for cereal porridge manufacturing (greatest energy is consumed for steam generation). Finally, cost correlations have been also found to predict both production and capital cost for a specific throughput for all manufacturing methods and products assessed along this work.

Overall, this research work has shown how the shift in manufacturing paradigms can be approached as an engineering-based problem. This thesis has developed a methodology capable to assess and compare theoretical food processing scenarios, with different degree of decentralisation, in economic, social and environmental impact terms along a wide range of production rate. The main outcome is a flexible and robust tool that supports decision-making and strategic planning for food processing. It must be accounted that, despite the assumptions and parameters used here are taken from reliable sources, they may not fit a real industrial system with a high level of accuracy. However, the use of the tool by the main agents of food production, i.e. manufacturers and stakeholders, would provide first-hand data. The correctness of results would be this way improved, and the platform could assist them in the complex decision between centralised and decentralised systems.

7.3. Suggestions for future work

This work provides a basis for incorporating the remaining steps of the supply chain to the modelling. The transport costs for the materials and products have not been considered in detail here, and the increasing energy costs of transport may shift the profitability of the whole system, for example when considering the frozen supply chain needed for the completed ice cream. It would also be useful to consider seasonal demands –for example this work has assumed uniform consumption through the year, which may be true for baby food and bread but will not be true for ice cream. These assumptions made here have to an extent limited the validity of the conclusions of the work, and a study of the whole supply chain is a necessary next step.

The economic and environmental impact variations on the whole network generated by each manufacturing method would be therefore assessed. The synthesis of the network could be defined from a municipal level to national and European ones. Multi-period and multi-objective considerations to determine the optimal network and operation could be also included in a further optimisation of the model. Multi-period would account for the availability of the raw materials and the market demand of seasonal products. Multi-objective aims at evaluating tradeoffs between economic cost and environmental impact of such network, using metric such as the carbon footprint and LCA analysis. The outcome would provide the best manufacturing method from all the alternatives for each product evaluated. The scope of the platform can be also enhanced by the addition of more products (foods and no foods) with contrasting features –e.g. water content, energy cost in transportation and storage, etc.

Bibliography

List of references

Acero J., Burdio, J.M., Barragán, L.A., Navarro, D., Alonso, R., García, J.R., Monterde, F., Hernández, P., Llorente, S., Garde, I., The domestic induction heating appliance: an overview of recent research, 2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition (2008). https://doi.org/10.1109/APEC.2008.4522791

Adhikari, B., Shrestha, J.N., Shakya, S.R., Design and Simulation of a Solar Electricity Based Induction Cooker using Quasi Resonant Topology, Proceedings of IOE Graduate Conference (2017).

AEA, Energy and Environment, 2007. Resource use efficiency in food chains. http://sciencesearch.defra.gov.uk/Document.aspx?Document=WU0103_4830_FRA.pdf

Aikins, E.F., Ramanathan, U., Key factors of carbon footprint in the UK food supply chains: a new perspective of life cycle assessment", International Journal of Operations & Production Management (In press) (2020). https://doi.org/10.1108/IJOPM-06-2019-0478

Akbar, M., Itohara, T., Scheduling for sustainable manufacturing: A review, Journal of Cleaner Production 205 (2018) 866–883. https://doi.org/10.1016/j.jclepro.2018.09.100

Albrecht, C., Smithers, J. Reconnecting through local food initiatives? Purpose, practice and conceptions of 'value' (2018). Agriculture and Human Values, 35 (1), pp. 67-81.

Alibaba, Bakery food tunnel oven (2019) (accessed 04/11/2019). https://www.alibaba.com/product-detail/T-D-shanghai-tunnel-oven-for_60708752086.html?spm=a2700.7724857.main07.19.723f67aaSJtxeB&s=p

Almena[(a)], A., Fryer, P.J., Bakalis, S., López-Quiroga, E., Centralized and distributed food manufacture: A modeling platform for technological, environmental and economic assessment at different production scales, Sustainable Production and Consumption 19 (2019) 181–193. https://doi.org/10.1016/j.spc.2019.03.001

Almena[(b)], A., López-Quiroga, E., Fryer, P.J., Bakalis, S., Towards the decentralisation of food manufacture: effect of scale production on economics, carbon footprint and energy demand, Energy Procedia 161 (2019) 182–199. https://doi.org/10.1016/j.egypro.2019.02.080

Almena[(c)], A., Goode, K.R., Bakalis, S., Fryer, P.J., López-Quiroga, E., Optimising food dehydration processes: energy efficient drum-dryer operation, Energy Procedia 161 (2019) 174–181. https://doi.org/10.1016/j.egypro.2019.02.078

Almena, A., Fryer, P.J., Bakalis, S., López-Quiroga, E., Local and decentralized scenarios for ice cream manufacture: a model-based assessment at different production scales, Journal of Food Engineering 286 (2020) 110099. https://doi.org/10.1016/j.jfoodeng.2020.110099

Almena, A., Lopez-Quiroga, E., Theodoropoulos, C., Fryer, P.J, Bakalis, S., Modelling, simulation and economical evaluation of dry food manufacture at different production scales, Comput. Aided Chem. Eng. 40 (2017) 787–792. https://doi.org/10.1016/B978-0-444-63965-3.50133-1.

Almena, A., Martin, M., Technoeconomic analysis of the production of epichlorohydrin from glycerol, Ind. Eng. Chem. Res. 55 (2016) 3226–3238. https://doi.org/10.1021/acs.iecr.5b02555.

Alonso-Almeida, M.M., Perramon, J., Bagur-Femenías, L., Shedding light on sharing ECONOMY and new materialist consumption: An empirical approach, Journal of Retailing and Consumer Services 52 (2020) (101900) 1–9. https://doi.org/10.1016/j.jretconser.2019.101900

Angeles-Martinez, L., Theodoropoulos, C., Lopez, Quiroga, E., Fryier, P.J., Bakalis, S., The Honeycomb model: A platform for systematic analysis of different manufacturing scenarios for fast moving consumer goods, Journal of Cleaner Production 193 (2018) 315–326. https://doi.org/10.1016/j.jclepro.2018.04.075

Aplevicz, K. S., Mazo, J. Z., Santos Neto, N. K. dos, Nalevaiko, F. S., & Sant´AnnaE. S. (2014). Evaluation of sourdoughs for the production of bread using spontaneous fermentation technique. Acta Scientiarum Technology, 36(4), 713-719. https://doi.org/10.4025/actascitechnol.v36i4.19703

Apte, U.M., Goh, C-H., Applying lean manufacturing principles to information intensive services, Int. J. Services Technology and Management 5 (2004) 488–506. https://doi.org/10.1504/IJSTM.2004.006280

Arellano[b], M., Benkhelifa, H., Alvarez, G., Flick, D., Coupling population balance and residence time distribution for the ice crystallization modeling in a scraped surface heat exchanger, Chemical Engineering Science 102 (2013) 502–513. http://dx.doi.org/10.1016/j.ces.2013.08.027

Arellano, A.[a], Flick, D., Benkhelifa, H., Alvarez, G., Rheological characterisation of sorbet using pipe rheometry during the freezing process, Journal of Food Engineering 119 (2013) 385–394. https://doi.org/10.1016/j.jfoodeng.2013.05.017

Asda (2019) (accessed 30/09/2019) https://www.asda.com

Balcombe, K., Fraser, I., Lowe, B., Souza-Monteiro, D., Information customization and food choice, American Journal of Agricultural Economics 98 (2016) 54–73. https://doi.org/10.1093/ajae/aav033

Baldea, M., Edgar, T.F., Stanley, B.L., Kiss, A.A., Modular Manufacturing Processes: Status, Challenges, and Opportunities, AIChE Journal 63 (10) (2017). https://doi.org/10.1002/aic.15872

Ballou, R.H., The evolution and future of logistics and supply chain management, Production 16 (2006) 375–386. http://dx.doi.org/10.1590/S0103-65132006000300002

Bao, J., Sun, M., Corke, H., Analysis of genotypic diversity in starch thermal and retrogradation properties in nonwaxy rice, Carbohydr. Polym. 67 (2006) 174–181. https://doi.org/10.1016/j.carbpol.2006.05.011.

Bayareh, M., Pordanjani, A.H., Nadooshan, A.A., Dehkordi, K.S., Numerical study of the effects of stator boundary conditions and blade geometry on the efficiency of a scraped surface heat exchanger, Applied Thermal Engineering 113 (2017) 1426–1436. http://dx.doi.org/10.1016/j.app lthermaleng.2016.11.166

Ben & Jerry, The Footprint of Your Pint (2016) (accessed 30/09/2019) https://www.benjerry.com /values/issues-we-care-about/climate-justice/life-cycle-analysis

Ben-Yoseph, E., Hartel, R.W., Computer simulation of ice recrystallization in ice cream during storage, Journal of Food Engineering 38 (1998) 309–331. https://doi.org/10.1016/S0260-8774(98)00116-2

Berick, A., Heat Losses In A Cook Pot at Constant Temperature, Aprovecho Research Center (2006)

Bianchi, P., Labory, S., Manufacturing regimes and transitional paths: Lessons for industrial policy, Structural Change and Economic Dynamics 48 (2019) 24–31. https://doi.org/10.1016/j.strueco.2017.10.003

Biegler, L.T., Grossmann, I.E., Westerberg, A.W., Systematic Methods of Chemical Process Design, Prentice Hall PTR, New Jersey, 1997. ISBN: 0-13-492422-3

Bielenberg, J., Palou-Rivera, I., The RAPID Manufacturing Institute–Reenergizing US efforts in process intensification and modular chemical processing, Chemical Engineering & Processing: Process Intensification 138 (2019) 49–54. https://doi.org/10.1016/j.cep.2019.02.008

Bitjoka, L., Tchatchueng, J.B., Libouga, D.G., Measurement of the moisture content of the granulated sugar by infrared transphotometry, Afr. J. Biotechnol. 6 (2007) 120–122. https://doi.org/10.5897/AJB06.644

Blay-Palmer, A., Donald, B., A Tale of Three Tomatoes: The New Food Economy in Toronto, Canada, Economic Geography 82 (2006) 383–399. https://doi.org/10.1111/j.1944-8287.2006.tb00322.x

Boccardi, G., Celata, G.P., Lazzarini, R., Saraceno, L., Trincheri, R., Development of a heat transfer correlation for a Scraped-Surface Heat Exchanger, Applied Thermal Engineering 30 (2010) 1101–1106. https://doi.org/10.1016/j.applthermaleng.2010.01.023

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., Product design and business model strategies for a circular economy, Journal of Industrial and Production Engineering 33 (2016) 308–320. http://dx.doi.org/10.1080/21681015.2016.1172124

Bocquet-Appel, J.P., When the World's Population Took Off: The Springboard of the Neolithic Demographic Transition, Science 29 (2011) 560–561. https://doi.org/10.1126/science.1208880

Bonanno, A., Buschm L., Handbook of the International Political Economy of Agriculture and Food, Edward Elgar Publishing Limited, UK and USA, 2015. ISBN: 978-1-78254-826-3.

Bongers, P. M.M., A heat transfer model of scraped surface heat exchanger for ice cream, Computer Aided Chemical Engineering, 21 (2006) 539-544. https://doi.org/10.1016/S1570-7946(06)80101-X

Bredariol, P., Spatti, M., Vanin, F.M., Different baking conditions may produce breads with similar physical qualities but unique starch gelatinization behaviour, LWT 111 (2019) 737–743. https://doi.org/10.1016/j.lwt.2019.05.094

Brodt, S., Kramer, J.K., Kendall, A., Feenstra, G., Comparing environmental impacts od regional and national-scale food supply chains: A case study of processed tomatoes, Food Policy 42 (2013) 106–114. https://doi.org/10.1016/j.foodpol.2013.07.004

Buchholz, S., Future manufacturing approaches in the chemical and pharmaceutical industry, Chemical Engineering and Processing 49 (2010) 993–995. https://doi.org/10.1016/j.cep.2010.08.010

Buksa, K., Application of model bread baking in the examination of arabinoxylan—protein complexes in rye bread, Carbohydrate Polymers 148 (2016) 281–289. https://doi.org/10.1016/j.carbpol.2016.04.071

Busch, K.G., Chapter 7: German Bread and Related Process Technology. In: McElhatton, A., El Idrissi, M.M., Kristbergsson, K. (eds.) Modernization of Traditional Food Processes and Products, Springer, New York, 2016. https://doi.org/10.1007/978-1-4899-7671-0

Business Dictionary. Definition of manufacturing. WebFinance, Inc. (2019) http://www.businessdictionary.com/definition/manufacturing.html (accessed 03/01/2019)

Butler, S. [(a)], As sliced bread sales fall and costs rise, are UK's leading bakers toast?, The Guardian (2017) (accessed 30/12/2019). https://www.theguardian.com/business/2017/nov/11/are-uks-leading-bakers-toast-bread-sales-fall-costs-rise

Butler, S.[(b)], Ice-cream demand fires up supermarket sales in June (2017). https://www.theguardian.com/lifeandstyle/2017/jun/27/ice-cream-and-booze-fire-up-uk-supermarkets

Byrd, R.H., Gilbert, J.C., Nocedal, J., A trust region method based on interior point techniques for nonlinear programming, Mathematical Programming 89 (2000) 149–185. https://doi.org/10.1007/PL00011391

Calderbank, P.H., Moo-Young, M.B., The prediction of power consumption in the agitation of non-Newtonian fluids. Trans. Inst. Chem. Eng. 37 (1959) 26–33

Calegari, L.P., Avalone, M.C., Fettermann, D.C., Barriers and enablers to food mass customization, Journal of Agribusiness in Developing and Emerging Economies (In press) (2020). https://doi.org/10.1108/JADEE-08-2019-0116

Campbell, G.M., Rielly, C.D., Fryer, P.J., Sadd, P.A., Measurement and Interpretation of Dough Densities, Cereal Chemistry 70 (5) (1993) 517-521.

Campesi, A., Cerri, M.O., Hokka, C.O., Badino, A.C., Determination of the average shear rate in a stirred and aerated tank bioreactor, Bioprocess and Biosystems Engineering 32 (2009) 241–248. https://doi.org/10.1007/s00449-008-0242-4

Carbon Trust, Industrial Energy Efficiency Accelerator, Guide to the industrial bakery sector (2011). https://www.carbontrust.com/media/206476/ctg034-bakery-industrial-energy-efficiency.pdf

Carocho, M., Morales, P., Ciudad-Mulero, M., Fernández-Ruiz, V., Ferreira, F., Heleno, S., Rodrigues, P., Barros, L., Ferreira, I.C.F.R., Comparison of different bread types: Chemical and physical parameters, Food Chemistry 310 (2020) 1–8. https://doi.org/10.1016/j.foodchem.2019.125954

Carson, J.K., Review of effective thermal conductivity models for foods, International Journal of Refrigeration 29 (2006) 958–967. https://doi.org/10.1016/j.ijrefrig.2006.03.016

Cerrada-Serra, P., Moragues-Faus, A., Zwart, T.A., Adlerova, B., Ortiz-Miranda, D., Avermaete, T., Exploring the contribution of alternative food networks to food security. A comparative analysis. Food Security 10 (6) (2018) 1371–1388. http://dx.doi.org/10.1007/s12571-018-0860-x

Challagulla, N.V., Rohatgi, V., Sharma, D., Kumar, R., Recent developments of nanomaterial applications in additive manufacturing: a brief review, Current Opinion in Chemical Engineering 28 (2020) 75–82. https://doi.org/10.1016/j.coche.2020.03.003

Chen, Z.L., Solution Algorithms for the Parallel Replacement Problem under Economy of Scale, Naval Research Logistics 45 (1998) 279-294. https://doi.org/10.1002/(SICI)1520-6750(199804)45:3<279::AID-NAV3>3.0.CO;2-4

Chhanwal, N., Anandharamakrishnan, C., Temperature- and Moisture-Based Modeling for Prediction of Starch Gelatinization and Crumb Softness during Bread-Baking Process, Journal of Texture Studies 45 (6) (2014) 462–476. https://doi.org/10.1111/jtxs.12097

Chhanwal, N., Bhushette, P.R., Anandharamakrishnan, C., Current Perspectives on Non-conventional Heating Ovens for Baking Process—a Review, Food and Bioprocess Technology 12 (2019) 1–15. https://doi.org/10.1007/s11947-018-2198-y

Chidmi, B., Murova, O., Measuring market power in the supermarket industry: the case of the Seattle–Tacoma fluid milk market. Agribusiness 27 (4) (2011) 435–449. http://dx.doi.org/10.1002/agr. 20276

Chiffoleau, Y., Millet-Amrani, S., Rossi, A., Rivera-Ferre, M.G., Lopez-Merino, P., The participatory construction of new economic models in short food supply chains, Journal of Rural Studies 68 (2019) 182–190. https://doi.org/10.1016/j.jrurstud.2019.01.019

Choi, Y., Okos, M.R, Effects of Temperature and Composition on the Thermal Properties of Foods. In: Le Maguer, L., Jelen, P., Food Engineering and Process Applications, Vol. 1: Transport Phenomena (pp. 93–101), Elsevier Applied Science Publishers, London, 1986. ISBN: 978-1-851-66022-3.

Cholette, S., Venkat, K., The energy and carbon intensity of wine distribution: A study of logistical options for delivering wine to consumers, Journal of Cleaner Production 17 (2009) 1401–1413. https://doi.org/10.1016/j.jclepro.2009.05.011

CIBO: Council of Industrial Boiler Owners. Energy Efficiency & Industrial Boiler Efficiency – An Industry Perspective (2003) (accessed 28/11/2018). http://invenoinc.com/wp-content/uploads/2017/05/CIBO-Steam-System-Efficiency-and-Boilers.pdf

Cipolla, C.M., Before the Industrial Revolution. European Society and Economy, 1000 – 1700, third ed., Taylor & Francis Group, London, 2003. ISBN: 978-0-393-31198-3

Cogné, C., Andrieu, J., Laurent, P., Besson, A., Nocquet, J., Experimental data and modelling of thermal properties of ice creams, Journal of Food Engineering 58 (2003) 331–341. https://doi.org/10.1016/S0260-8774(02)00396-5

Coley, D., Howard, M., Winter, M., Local food, food miles and carbon emissions: A comparison of farm shop and mass distribution approaches, Food Policy 34 (2) (2009) 150–155. https://doi.org/10.1016/j.foodpol.2008.11.001

Cope, S., Artisanal Food Production and Craft. In: Thompson P.B., Kaplan D.M. (eds) Encyclopedia of Food and Agricultural Ethics. Springer, Dordrecht, 2014. https://doi.org/10.1007/978-94-007-0929-4

Córdoba, A., Quantitative fit of a model for proving of bread dough and determination of dough properties, Journal of Food Engineering 96 (2010) 440–448. https://doi.org/10.1016/j.jfoodeng.2009.08.023

Corsini, A., Bonacina, F., De Propris, L., Feudo, S., Marchegiani, A., Multivariate performance indicator of baking process, Energy Procedia 82 (2015) 554–561. https://doi.org/10.1016/j.egypro.2015.11.869

Cottee, J., LNN Food Feasibility Project Final Report. Local Nexus Network for Redistributed Manufacturing, 2014. http://localnexus.org/wp-content/uploads/2015/04/LNN-Food-Feasibility-Report-final-for-web.pdf (accessed 11/06/2019).

Coulson, J.M., Richardson, J.F., Backhurst, J.R., Harker, J.H., Fluid Flow, Heat Transfer and Mass Transfer. Vol. 1. In: Coulson, J.M., Richardson, J.F. (eds.) Chemical Engineering (6th edition), Butterworh Heinemann, London, 1999. ISBN: 0-7506-4444-3.

Cox, A., Chicksand, D., The Limits of Lean Management Thinking: Multiple Retailers and Food and Farming Supply Chains, European Management Journal 23 (6) (2005) 648–662. https://doi.org/10.1016/j.emj.2005.10.010

Crundwell, A. UK Industry Reports, Ice Cream Production, Ibis World March, 2019. http://clients1.ibisworld.co.uk/reports/uk/industry/default.aspx?entid=555

Curtis, F., Eco-localism and sustainability, Ecol. Econ. 46 (2003) 83–102. https://doi.org/10.1016/S0921-8009(03)00102-2

Da Silveira, G., Borenstein, D., Fogliatto, F.S., Mass customization: Literature review and research directions, Int. J Production Economics 72 (2001) 1–13. https://doi.org/10.1016/S0925-5273(00)00079-7

Dal Bello, F., Clarke, C.I., Ryan, L.A.M., Ulmer, H., Schober, T.J., Ström, K., Sjögren, J., van Sinderen, D., Schnürer, J., Arendt, E.K., Improvement of the quality and shelf life of wheat bread by fermentation with the antifungal strain Lactobacillus plantarum FST 1.7, Journal of Cereal Science 45 (3) (2007) 309–318. https://doi.org/10.1016/j.jcs.2006.09.004

Davidson, I., Chapter 5 - Oven Designs. In: Davidson, I. (ed.) Biscuit Baking Technology. Processing and Engineering Manual (2nd edition), Elsevier, London, 2016. https://doi.org/10.1016/B978-0-12-804211-3.00005-4

Davis, E. S., Heat Transfer and Pressure Drop in Annuli, Transactions of ASME (1943) 755–760.

De Boni, A., Pasqualone, A., Roma, P., Acciani, C., Traditions, health and environment as bread purchase drivers: A choice experiment on high-quality artisanal Italian bread, Journal of Cleaner Production 221 (2019) 249–260. https://doi.org/10.1016/j.jclepro.2019.02.261

De Stefano, V., The rise of the “just-in-time workforce”: on-demand work, crowdwork and labour protection in the “gig-economy”, Comp. Labor Law Policy J. 37 (2016) 471–504. http://dx.doi.org/10.2139/ssrn.2682602

DEFRA[a]: Department for Environment Food and Rural Affairs, 2019. Food Statistics in your pocket: Food Chain. https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-food-chain.

DEFRA[b]: Department for Environment Food and Rural Affairs, 2019. Total Factor Productivity of the United Kingdom Food Chain 2017. https://www.gov.uk/government/publications/food-chain-productivity/total-factor-productivity-of-the-united-kingdom-food-chain-2016-provisional-release

DEFRA: Department for Environment Food and Rural Affairs, 2013. Food Statistics Pocketbook 2013. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/315418/foodpocketbook-2013update-29may14.pdf

DEFRA: Department for Environment Food and Rural Affairs, 2017. Food Statistics Pocketbook 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/608426/foodpocketbook-2016report-rev-12apr17.pdf

Demartini, M., Pinna, C., Tonelli, F., Terzi, S., Sansone, C., Testa, C., Food industry digitalization: from challenges and trends to opportunities and solutions, IFAC-PapersOnLine 51 (2018) 1371–1378. https://doi.org/10.1016/j.ifacol.2018.08.337

Deosarkar, S.S., Khedkar, C.D., Kalyankar, S.D., Sarode, A.R., Ice cream: Uses and Method of Manufacture, Encyclopedia of Food and Health (2016) 391-397. https://doi.org/10.1016/B978-0-12-384947-2.00384-6

Department for Business, Energy and Industrial Strategy. Digest of United Kingdom Energy Statistics (DUKES) July 2018 London, UK, 2019. https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2019

Department for Transport, Domestic Road Freight Statistics, United Kingdom 2017. London, UK (2018) (accessed 02/07/2020) https://www.gov.uk/government/statistics/road-freight-statistics-2017

Desmazzery, B., Classic white loaf recipe (2008) (accessed 04/11/2019) https://www.bbcgoodfood.com/recipes/7568/classic-white-loaf

Dick, A., Bhandari, B., Prakash, S., 3D printing of meat, Meat Science 153 (2019) https://doi.org/10.1016/j.meatsci.2019.03.005

Dodgson, M., Gann. D., Salter, A., Think, Play, Do: Innovation, Technology, and Organization. Oxford University Press, Oxford, 2005. ISBN: 978-0-199-26809-2

Dokko, J., Mumford, M., Schanzenbach, D.W., Workers and the online gig economy. The Hamilton project. The Brooking Institution (2015) (accessed 18/04/2018). http://www.hamiltonproject.org/assets/files/workers_and_the_online_gig_economy.pdf

Donaher, E., Lynes, J., Is local produce more expensive? Challenging perceptions of price in local food systems, The International Journal of Justice and Sustainability 22 (2017) 746–763 https://doi.org/10.1080/13549839.2016.1263940

Douglas, J.M., Conceptual Design of Processes, McGraw-Hill, New York, 1988. ISBN: 0-07-017762-7

Doyennette, M., Aguayo-Mendoza, M.G., Williamson, A.M., Martins, S. I.F.S., Stieger, M., Capturing the impact of oral processing behaviour on consumption time and dynamic sensory perception of ice creams differing in hardness, Food Quality and Preference 78 (2019) 103721. https://doi.org/10.1016/j.foodqual.2019.103721

Duarte, G.T., de Alencar Nääs, I., Innocencio, C.M., da Silva Cordeiro, A.F., Rodrigues da Silva, R.B.T., Environmental impact of the on-road transportation distance and product volume from farm to a fresh food distribution center: a case study in Brazil. Environmental Science and Pollution Research 26 (2019) 33694–33701. https://doi.org/10.1007/s11356-019-06461-8

Dufour, B., Social impact measurement: What can impact investment practicesand the policy evaluation paradigm learn from each other?, Research in International Business and Finance 47 (2019) 18–30. https://doi.org/10.1016/j.ribaf.2018.02.003

Egilmez, G., Kucukvar, M., Tatari, O., Bhutta, M.K.S., Supply chain sustainability assessment of the U.S. food manufacturing sectors: A life cycle-based frontier approach, Resources, Conservation and Recycling 82 (2014) 8–20. https://doi.org/10.1016/j.resconrec.2013. 10.008

Energy Information Administration, EIA. International Energy Outlook 2019. Table: Food Industry Energy Consumption, 2019. https://www.eia.gov/outlooks/ieo/tables_ref.php

Engelund, E.H., Breum, G., Friis, A., Optimisation of large-scale food production using Lean Manufacturing principles, Journal of Foodservice 20 (1) 2009 4–14. https://doi.org/10.1111 /j.1748-0159.2008.00109.x

Elhweg, B., Burns, I.W., Chew, Y.M.J., Martin, P.J., Russell, A.B., Wilson D.I., Viscous dissipation and apparent wall slip in capillary rheometry of ice cream, Food and bioproducts processing 87 (2009) 266–272. https://doi.org/10.1016/j.fbp.2008.11.002

Ellis, V., Bosworth, G., Supporting rural entrepreneurship in the UK microbrewery sector, Brit. Food J. 117 (2015), 2724–2738. https://doi.org/10.1108/BFJ-12-2014-0412.

Esmaeilian, B., Behdad, S., Wang, B., The evolution and future of manufacturing: A review, Journal of Manufacturing Systems 39 (2016) 79–100. https://doi.org/10.1016/j.jmsy.2016.03.001

European Environment Agency (EEA), The European environment – State and outlook 2020: Knowledge for transition to a sustainable Europe, Luxemburg, 2019. https://doi.org/10.2800/96749

Eurostat. Manufacturing statistics - NACE Rev. 2. (2019). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Manufacturing_statistics_-_NACE_Rev._2 (accessed 14/05/2019).

Evans, J.A., Huet, J-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Bond, C., Scheurs, M., Van Sambeek, T.W.M., Cold store energy usage and optimisation, ICR Proceedings (2011) 1–10.

Fahimnia B., Farahani R.Z., Marian R., Luong L., A review and critique on integrated production-distribution planning models and techniques. Journal of Manufacturing Systems 32 (2013) 1–19. https://doi.org/10.1016/j.jmsy.2012.07.005

FAO, The future of food and agriculture – Trends and challenges. Rome, Italy: Food and Agriculture Organization of the United Nations, 2017

Femmer, T., Kuehne, A.J.C., Wessling, M., Estimation of the structure dependent performance of 3-D rapid prototyped membranes, Chemical Engineering Journal 273 (2015) 438–445 https://doi.org/10.1016/j.cej.2015.03.029.

Ferguson, S.M., Olewnik, A.T., Cormier, P., A review of mass customization across marketing, engineering and distribution domains toward development of a process framework, Research in Engineering Design 25 (1) (2014) 11–30. https://doi.org/10.1007/s00163-013-0162-4

Fernqvist, F., Ekelund, L., Credence and the effect on consumer liking of food – A review, Food Quality and Preference 32 (2014) 340–353. https://doi.org/10.1016/j.foodqual.2013.10.005

Fisher, K., James, K., Sheane, R., Nippress, J., Allen, S.R., Cherruault, J., Fishwick, M., Lillywhite, R., Sarrouy, C., An initial assessment of the environmental impact of grocery products, Waste and Resources Action Programme, Banbury, 2013.

Flick, D., Doursat, C., Grenier, D., Lucas, T., Modelling of baking processes. In: Bakalis, S., Knoezer, K., Fryer, P. (eds.) Modeling Food Processing Operations, Woodhead Publishing, Cambridge, 2015. http://dx.doi.org/10.1016/B978-1-78242-284-6.00005-2

Floros, J.D., Newsome, R., Fisher, W., Barbosa-Canovas, G.V., Chen, H., Dunne, P., German, J.B., Hall, R.L., Heldman, D.R., Karwe, M.V., Knabel, S.J., Labuza, T.P., Lund, D.B., Newell-McGloughlin, M., Robinson, J.L., Sebranek, J.G., Shewfelt, R.L., Tracy, W.F., Weaver, C.M., Ziegler, G.R., Feeding the world today and tomorrow: the importance of food science and technology, Compr Rev Food Sci Food Saf 9 (2010) 572–99. https://doi.org/10.1111/j.1541-4337.2010.00127.x

FoB, Federation of Bakers, The UK Bakery market, (2016) (accessed 14/01/2020) https://www.fob.uk.com/about-the-bread-industry/

Foo, D.C.Y., Elyas, R., Chapter 1 - Introduction to Process Simulation. In: Foo, D.C.Y., Chemmangattuvalappil, N., Ng, D.K.S., Elyas, R., Chen, C.L., Elms, R.D., Lee, H.Y., Chien, I.L., Chong, S., Chong, C.H. (eds), Chemical Engineering Process Simulation, Elsevier, 2017. https://doi.org/10.1016/B978-0-12-803782-9.00001-7

Fornberg, B., Generation of Finite Difference Formulas on Arbitrarily Spaced Grids, Mathematics of Computation 51 (184) (1988) 699–706. https://doi.org/10.1090/S0025-5718-1988-0935077-0

Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B., Flynn A., Mylan, J., Environmental Impacts of Food Production and Consumption: A report to the Department for Environment, Food and Rural Affairs, Manchester Business School, Defra, London, 2006.

Fredrickson, A.G., Bird, R.B., Non-newtonian flow in annuli, Industrial and Engineering Chemistry 50 (3) (1958) 347–52. https://doi.org/10.1021/ie50579a035

Freeman, R., McMahon, C., The Potential Role of Re-Distributed Manufacturing in Improving Industrial Sustainability. In: Reference Module in Materials Science and Materials Engineering, Elsevier, 2019. https://doi.org/10.1016/B978-0-12-803581-8.10910-5

Frenken, K., Political economies and environmental futures for the sharing economy, Philos. Trans. Royal Soc. A – Math. Phys. Eng. Sci. 375 (2017) Issue 2095. https://doi.org/10.1098/rsta.2016.0367

Fricke, B.A., Becker, B.R., Evaluation of Thermophysical Property Models for Foods. HVAC&R Research 7 (4) (2001) 311-330. https://doi.org/10.1080/10789669.2001.10391278

Gabriel, L.F., Santana-Ribeiro, L.C. de, Economic growth and manufacturing: An analysis using Panel VAR and intersectoral linkages, Structural Change and Economic Dynamics 49 (2019) 43–61. https://doi.org/10.1016/j.strueco.2019.03.008

Galli, F., Brunori, G., Short Food Supply Chains as drivers of sustainable development. Evidence Document. Document developed in the framework of the FP7 project FOODLINKS (GA No.265287). Laboratorio di studi rurali Sismondi, 2013. ISBN 978-88-90896-01-9.

Gally, T., Rounaud, O., Jury, V., Havet, M., Ogé, A., Le-Bail, A., Proofing of bread dough assisted by ohmic heating, Innovative Food Science and Emerging Technologies 39 (2017) 55–62. http://doi.org/10.1016/j.ifset.2016.11.008

Gao, J., Si-Koh, A.H., Tay, S.L., Zhou, W., Dough and bread made from high- and low-protein flours by vacuum mixing: Part 1: Gluten network formation, Journal of Cereal Science 74 (2017) 288 – 295. https://doi.org/10.1016/j.jcs.2017.03.008

Garcia, S., Trinh, C.T., Modular design: Implementing proven engineering principles in biotechnology, Biotechnology Advances (2019) (In press). https://doi.org/10.1016/j.biotechadv.2019.06.002

Garrehy, P., Centralised vs Decentralised Manufacturing, Industry Today 17 (2014) 28-39. https://industrytoday.com/centralized-vs-decentralized-manufacturing/

Gellynck, X., Kühne, B., Van Bockstaele, F., Van de Walle, D., Dewettinck, K., Consumer perception of bread quality, Appetite 53 (1) (2009) 16–23. https://doi.org/10.1016/j.appet.2009.04.002

Giampetri, E., Verneau, F., Del Giudice, T., Carfora, V., Finco, A., A Theory of Planned behaviour perspective for investigating the role of trust in consumer purchasing decision related to short food supply chains, Food Quality and Preference 64 (2018) 160–166. https://doi.org/10.1016/j.foodqual.2017.09.012

Gill, A., Cost Estimation Model for Polyacrylonitrile-Based Carbon Fiber Manufacturing Process. Journal of manufacturing science and engineering 139 (4) (2017) 1087-1357. https://doi.org/10.1115/1.4034713

Giménez, A., Varela, P., Salvador, A., Ares, G., Fiszman, S., Garitta, L., Shelf life estimation of brown pan bread: A consumer approach, Food Quality and Preference 18 (2007) 196–204. https://doi.org/10.1016/j.foodqual.2005.09.017

Gisslen, W., Professional Baking (7th Edition), John Wiley and Sons Inc., USA, 2016. ISBN: 978-1-119-19532-0.

Gleim, M.R., Johnson, C.M., Lawson, S.J., Sharers and sellers: A multi-group examination of gig economy workers' perceptions, Journal of Business Research 98 (2019) 142–152. https://doi.org/10.1016/j.jbusres.2019.01.041

Godfrey, J.C. Static Mixers. Chapter 12. In: Harnby, N., Edwards, M.F., Nienow, A.W., (eds.), Mixing in the Process Industries (2nd edition), Butterworth and Co., Oxford, 1997. https://doi.org/ 10.1016/B978-075063760-2/50033-0

Godoi, F.C., Prakash, S, Bhandari, B.R., 3d printing technologies applied for food design: Status and prospects, Journal of Food Engineering 179 (2016) 44–54. http://dx.doi.org/10.1016/j.jfoodeng.2016.01.025

Goff, H.D., Colloidal aspects of Ice Cream – A Review. International Dairy Journal (7) (1997) 363–373. https://doi.org/10.1016/S0958-6946(97)00040-X

Goff, H.D., Davidson, V.J., Cappi, E., Viscosity of ice cream mix at pasteurization temperatures, Journal of Dairy Science 77 (2004) 2207–2213. https://doi.org/10.3168/jds.S0022-0302(94)77163-0

Goff, H.D., Davidson, V.J., Flow characteristics and holding time calculations of ice cream mixes in HTST holding tubes, J. Food Prot. 55 (1992) 34–37. https://doi.org/10.4315/0362-028X-55.1.34

Goff, H.D., Hartel, R.W, Ice Cream (7th edition), Springer, New York, 2013. ISBN 978-1-4614-6096-1.

Gondzio, J., Interior point methods 25 years later, European Journal of Operational Research 218 (2012) 587–601. https://doi.org/10.1016/j.ejor.2011.09.017

Goodier, M., Ice cream van capitals of UK revealed - see if your town makes the list (2019) (accessed 30/09/2019) https://www.mirror.co.uk/news/uk-news/ice-cream-van-capitals-uk-18784887

Government of United Kingdom. Corporation Tax rates and reliefs (2019b) (accessed: 10/10/2017) https://www.gov.uk/corporation-tax-rates/rates.

Government of United Kingdom. Food products (VAT Notice 701/14) (2019a) (accessed: 10/10/2019). https://www.gov.uk/guidance/food-products-and-vat-notice-70114

Government of United Kingdom. Food Statistics in your pocket: Food Chain (2019d) (accessed 14/01/2020). https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-food-chain#agri-food-sector-employees-gb-q3-2018

Government of United Kingdom. Greenhouse gas reporting: conversion factors 2017 (2017c) (accessed: 06/05/2017). https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017.

Government of United Kingdom. Greenhouse gas reporting: conversion factors 2019 (2019c) (accessed 15/03/2019). https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversio n-factors-2019.

Government of United Kingdom. Land value estimates for policy appraisal (2015) (accessed 8/12/2016) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/407155/February_2015_Land_value_publication_FINAL.pdf

Government of United Kingdom. Tax on shopping and services (2017a) (accessed: 06/04/2017). https://www.gov.uk/tax-on-shopping/vat-duties.

Govindan, K. Sustainable consumption and production in the food supply chain: A conceptual framework, International Journal of Production Economics 195 (2018) 419–431. https://doi.org/10.1016/j.ijpe.2017.03.003

Gray, J.A., Bemiller, J.N., Bread Staling: Molecular Basis and Control, Comprehensive Reviews in Food Science and Food Safety 2 (2006) 1–21. https://doi.org/10.1111/j.1541-4337.2003.tb00011.x

Grebitus, C., Lusk, J.L., Nayga Jr., R.M., Effect of distance of transportation on willingness to pay for food, Ecological Economics 88 (2013) 67–75. https://doi.org/10.1016/j.ecolecon.2013.01.006

Green, D.W., Perry, R.H., Perry's Chemical Engineering Handbook (8th ed) The McGraw Hill Companies, 2008 [ebook]. https://doi.org/10.1036/0071422943

Grenier, Al., Monteau J.Y., Le Bail, A., Hayert, M., Effect of external conditions on the rate of post-baking chilling of bread, Journal of Food Engineering 55 (1) (2002) 19–24. https://doi.org/10.1016/S0260-8774(01)00224-2

Grossmann, I.E., Global Optimization in Engineering Design, Springer, Boston, 1996. https://doi.org/10.1007/978-1-4757-5331-8

Grossmann, I.E., Westerberg, A.W., Research Challenges in Process Systems Engineering, AIChE Journal 46 (9) (2000) 1698–1703. https://doi.org/10.1002/aic.690460902

Groves, A.M., Authentic British food products: a review of consumer perceptions. International Journal of Consumer Studies 25 (3) (2001) 246–254. http://dx.doi.org/10.1046/j.1470-6431.2001.00179.x

Gurvich, I., Lariviere, M., Moreno, A., Operations in the On-Demand Economy: Staffing Services with Self-Scheduling Capacity. In: Hu, M. (eds), Sharing Economy. Springer Series in Supply Chain Management 6, Springer, Cham, 2019. https://doi.org/10.1007/978-3-030-01863-4_12

Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D.A., Jawahir, I.S., Clarens, A.F., Rickli, J.L., A Review of Engineering Research in Sustainable Manufacturing, Journal of Manufacturing Science and Engineering 135 (4) (2013) 1–16. https://doi.org/10.1115/1.4024040

Hale, J., Legun, K., Campbell, H., Carola, M., Social sustainability indicators as performance, Geoforum 103 (2019) 47–55. https://doi.org/10.1016/j.geoforum.2019.03.008

Hamari, J., Sjöklint, M., Ukkonen, A., The sharing economy: why people participate in collaborative consumption, J. Assoc. Inf. Sci. Technol. 67 (9) (2016) 2047–2059. https://doi.org/10.1002/asi.23552.

Hannibal, M., Knight, G., Additive manufacturing and the global factory: Disruptive technologies and T the location of international business, International Business Review 27 (2018) 1116–1127. https://doi.org/10.1016/j.ibusrev.2018.04.003

Harrison, R.P., Rafiq, Q.A., Medcalf, N., Centralised versus decentralised manufacturing and the delivery of healthcare products: A United Kingdom exemplar, Cytotherapy 20 (2018) 873-890. https://doi.org/10.1016/j.jcyt.2018.05.003

Hartel, R.W., Ice crystallization during the manufacture of ice cream, Trends in Food Science & Technology 7 (10) (1996) 315–321. https://doi.org/10.1016/0924-2244(96)10033-9

Hauer, E., The Art of Regression Modeling in Road Safety, Springer International Publishing, Switzerland, 2015. ISBN: 978-3-319-12528-2.

Hazarika, M., Disxit, U.S., Davim, J.P., Chapter 1 - History of Production and Industrial Engineering Through Contributions of Stalwarts. In: Davim, J.P. (ed) Manufacturing Engineering Education (2019) 1–29. https://doi.org/10.1016/B978-0-08-101247-5.00001-0

Hebeda, R.E., Zobel, H.Z., Baked Goods Freshness, Marcel Dekker Inc., New York, 1996. ISBN 0-8247-9348-X

Heldman, D.R., Lund, D.B., The Beginning, Current, and Future of Food Engineering: A Perspective. In: Aguilera J., Simpson R., Welti-Chanes J., Bermudez-Aguirre D., Barbosa-Canovas G. (eds) Food Engineering Interfaces. Food Engineering Series. Springer, New York, 2010. https://doi.org/10.1007/978-1-4419-7475-4_1

Helpman, E., International trade in the presence of product differentiation, economies of scale and monopolistic competition, J. Int. Econ. 11 (1981) 305–340. https://doi.org/10.1016/0022-1996(81)90001-5.

Hernández-Parra, O.D., Plana-Fattori, A., Alvarez, G., Ndoye, F.T., Benkhelifa, H., Flick, D., Modeling flow and heat transfer in a scraped surface heat exchanger during the production of sorbet, Journal of Food Engineering 221 (2018) 54–69. https://doi.org/10.1016/j.jfoodeng.2017.09.027

Hodge, G.L., Ross, K.G., Joines, J.A., Thoney, K., Adapting lean manufacturing principles to the textile industry, Production Planning & Control 22 (3) (2011) 237 –24. https://doi.org/10.1080/09537287.2010.498577

Homegrown, M., Why You Should Proof Bread in the Refrigerator (2013) (accessed 04/11/2019) https://www.rootsimple.com/2013/11/why-you-should-proof-bread-in-the-refrigerator/#comments

Hounshell, D.A., From the American System to Mass Production, 1800–1932, The Johns Hopkins University Press, USA, 1985. ISBN: 978-0-8018-2975-8.

Hu, J, Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization, Procedia CIRP 7 (2013) 3 – 8. https://doi.org/10.1016/j.procir.2013.05.002

Hu, S.J., Ko, J., Weyand, L., ElMaraghy, H.A., Lien, T.K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N., Shpitalni, M., Assembly system design and operations for product variety. CIRP Annals - Manufacturing Technology 60 (2011) 715–733. https://doi.org/10.1016/j.cirp.2011.05.004

Huet, E., Uber raises UberX commission to 25 percent in five more markets, Forbes (2015) (accessed: 12/27/2017). https://www.forbes.com/sites/ellenhuet/2015/09/11/uber-raises-uberx-commission-to-25-percent-in-five-more-markets/#b54bcfb32148.

IceTech, Gelato equipement (2019) (accessed 12/06/2019) http://www.icetechitaly.it/en/products/products.aspx

Jackson, B., Scargle, J.D., Barnes, D., Arabhi, S., Alt, A., Gioumousis, P., Gwin, E., Sangtrakulcharoen, P., Tan, L., Tsai, T.T., An algorithm for optimal partitioning of data on an interval, IEEE Signal Processing Letters, 12 (2) (2005) 105–108. https://doi.org/10.1109/LSP.2001.838216

Jarosz, L., The city in the country: growing alternative food networks in metropolitan areas. J. Rural Stud. 24 (2008) 231–244. http://dx.doi.org/10.1016/j.jrurstud.2007.10.002

Jewson. Sustainable timber and building materials supplier. Build Cost Calculator (2017) (accessed 8/12/2017) http://www.jewson.co.uk/working-with-you/for-self-builders/preliminary-planning/calculators/build-cost-calculator/

Jia, F., Wang, X., Mustafee, N., Hao, L., Investigating the feasibility of supply chain-centric business models in 3D chocolate printing: A simulation study, Technological Forecasting and Social Change 102 (2016) 202–213. https://doi.org/10.1016/j.techfore.2015.07.026

Jiang, P., Leng, J., The configuration of social manufacturing: a social intelligence way towards service-oriented manufacturing, International Journal of Manufacturing Research 12 (2017) 4–19. https://doi.org/10.1504/IJMR.2017.083647

Jindal, P., Zhu, T., Chintagunta, P., Dhar, S., Point-of-Sale Marketing Mix and Brand Performance – The moderating Role of Retail Format and Brand Type. (2018). Kilts Centre for Marketing at Chicago Booth – Nielsen Dataset Paper Series 2008. Last revised 21 Feb 2018. Available at SSRN: https://ssrn.com/abstract=3127580.

Johnston, P., Everard, M., Santillo, D., Robèrt, K.H., Reclaiming the Definition of Sustainability, Env Sci Pollut Res 14 (1) (2007) 60 – 66. http://dx.doi.org/10.1065/espr2007.01.375

Kagermann, H., Change Through Digitization – Value Creation in the Age of Industry 4.0, In: Albach, H., Meffert, H., Pinkwart, A., Reichwald, R. (eds), Management of Permanent Change. Springer Gabler, Wiesbaden, 2014. https://doi.org/10.1007/978-3-658-05014-6_2

Kakish, J., Zhang, P-L., Zeid, I., Towards, the design and development of a knowledge-base universal modular jigs and fixtures system, Journal of Intelligent Manufacturing 11 (2000) 381–401. https://doi.org/10.1023/A:1008978319436

Kamonpatana, K., The Role of Food Industry in Improving Health, Encyclopedia of Food Security and Sustainability 2, (2019) 267–274. https://doi.org/10.1016/B978-0-08-100596-5.22050-7

Kapavarapu, V., Project optimization at a conceptual level by using Aspen HYSYS and Aspen Integrated Economics (2011), OPTIMIZE Conference Washington D.C., May 2011.

Keating, B.A., Herrero, M., Carberry, P.S., Gardner, J., Cole, M.B., Food wedges: Framing the global food demand and supply challenge towards 2050, Global Food Security 3 (2014) 125–132. https://doi.org/10.1016/j.gfs.2014.08.004

Kelly, J.D., Mann, J.L., Crude oil blend scheduling optimization: an application with multimillion dollar benefits – Part 2, Hydrocarbon Processing (July) (2003) 72–79

Kern, D.Q., Process Heat Transfer. International Student Edition, McGraw-Hill Company, Tokyo, 1983. ISBN 0-07-085353-3

Khatir, Z., Taherkhani, A.R., Paton, J., Thompson, H., Kapur, N., Toropov, V., Energy thermal management in commercial bread-baking using a multi-objective optimisation framework, Applied Thermal Engineering 80 (2015) 141–149. http://dx.doi.org/10.1016/j.applthermaleng.2015.01.042

Killick, R., Fearnhead, P., Eckley, I.A., Optimal detection of changepoints with a linear computational cost, Journal of the American Statistical Association 107 (500) (2012) 1590-1598. https://doi.org/10.1080/01621459.2012.737745

Kim, Y-H., Park, L.K., Yiacoumi, S., Tsouris, C., Modular Chemical Process Intensification: A Review, Annual Review of Chemical and Biomolecular Engineering 8 (2017) 359–380. https://doi.org/10.1146/annurev-chembioeng-060816-101354

Ko, Y.C., Lin, T.H., Emissions and efficiency of a domestic gas stove burning natural gases with various compositions, Energy Convers. Manag. 44 (2003) 3001–3014. https://doi.org/10.1016/S0196-8904(03)00074-8

Koenig, Bakery machines – tunnel oven (2019) (accessed 30/11/2019) https://www.koenig-rex.com/en/products/Baking/MDI_Stratos_EN.php

Kolesar, D., Aspen EDR helps troubleshoot thermosyphon problems at Dow (2010), AspenTech Global Conference, Boston, MA, May 2010.

Konstantas, A., Stamford, L, Azapagic, A., Environmental impacts of ice cream, Journal of Cleaner Production 209 (2019) 259–272. https://doi.org/10.1016/j.jclepro.2018.10.237

Kopanos, G. M., Puigjaner, L., Georgiadis, M.C., 2012. Efficient mathematical frameworks for detailed production scheduling in food processing industries. Computers and Chemical Engineering 42 (2012) 206–216. https://doi.org/10.1016/j.compchemeng.2011.12.015

Koren, Y., Shpitalni, M., Gu, P., Hu, S.J., Product Design for Mass-Individualization, Procedia CIRP 36 (2015) 64 – 71. https://doi.org/10.1016/j.procir.2015.03.050

Koren, Y., The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems, John Wiley & Sons Inc., USA, 2010. ISBN: 978-0-470-58377-7.

Kouki, C., Sahin, E., Jemaï, Z., Dallery, Y., Assessing the impact of perishability and the use of time temperature technologies on inventory management, International Journal of Production Economics 143 (2013) 72–85. https://doi.org/10.1016/j.ijpe.2010.09.032

Kühnle, H., Distributed Manufacturing: Paradigm, Concepts, Solutions and Examples. Springer, London, 2010. ISBN: 978-1-84882-707-3.

Kumano, H., Asaoka, T., Saito, A., Okawa, S., Study on latent heat of fusion of ice in aqueous solutions, International Journal of Refrigeration 30 (2007) 267–273. https://doi.org/10.1016/j.ijrefrig. 2006.07.008

Kumar, M., Tsolakis, N. Agarwal, A., Srai, J.S. Developing distributed manufacturing strategies from the perspective of product-process matrix. International Journal of Production Economics (2019) (In press) https://doi.org/10.1016/j.ijpe.2019.05.005

Kuznesof, S., Regional foods: a consumer perspective, British Food Journal 99 (6) (1997) 199–206. https://doi.org/10.1108/00070709710181531

Kuznesof, S., Tregear, A., Moxey, A., Regional foods: a consumer perspective, Brit. Food J. 99 (6) (1997) 199–206. https://doi.org/10.1108/00070709710181531

Ladha-Sabour, A., Bakalis, S., Fryer, P.J., Lopez-Quiroga, E., Mapping energy consumption in food manufacturing, Trends in Food Science & Technology 86 (2019) 270–280. https://doi.org /10.1016/j.tifs.2019.02.034

Lancaster, H.M., Moisture in malt, J. I. Brewing 29 (1923) 612–623. https://doi.org/10.1002/j.2050-0416.1923.tb06643.x

Landier, A., Nair, V.B., Wulf, J., Trade-offs in staying close: Corporate decision making and geographic dispersion. Review of Financial Studies 22 (3) (2009) 1119-1148. https://doi.org/10.1093/rfs/hhm042

Le-bail, A., Dessev, T., Jury, V., Zuniga, R., Park, T., Pitroff, M., Energy demand for selected bread making processes: Conventional versus part baked frozen technologies, Journal of Food Engineering 96 (2010) 510–519. https://doi.org/10.1016/j.jfoodeng.2009.08.039

Lefebvre, J., Finished Product Formulation, J. Am. Oil Chem. Soc. (60) (1983) 295–300. https://doi.org /10.1007/BF02543503

Lehtinen, U., Torkko, M., The Lean Concept in the Food Industry: A Case Study of Contract a Manufacturer, Journal of Food Distribution Research 36 (3) (2005) 57–67. https://doi.org/10.22004/ag.econ.27759

Leighton, A., On the calculation of the freezing point of ice cream mixes and of the quantities of ice separated during the freezing process, Journal of Dairy Science 10 (4) (1927) 300–308. https://doi.org/10.3168/jds.S0022-0302(27)93845-4

Leuliet, J.C., Maingonnat, J.F., Corrieu, G., Etude de la perte de charge dans un echangeur de chaleur à surface raclée traitant des produits newtoniens et non-newtoniens, Journal of Food Engineering 5 (1986) 153–176. https://doi.org/10.1016/0260-8774(86)90014-2

Li, L. Cooperative purchasing and preactive inventory sharing – Channel balancing and performance improvement, European Journal of Operational Research 278 (2019) 738–751. https://doi.org/10.1016/j.ejor.2018.11.063

Lin, A.H.M., Nichols, B.L., The digestion of complementary feeding starches in the young child, Starch 69 (2017) 17000012. https://doi.org/10.1002/star.201700012

Linnhoff, B., Pinch analysis – a state of the art overview, Chemical Engineering Research and Design 71 (Part A5) (1993) 503–522

Lipson, H., Kurman, M. Fabricated: The New World of 3D Printing, John Wiley & Sons Inc., Indianapolis, 2013. ISBN: 978-1-118-41694-5

Lipton, J.I., Cutler, M., Nigl, F., Cohen, D., Lipson, H., Additive manufacturing for the food industry, Trends in Food Science & Technology 43 (2015) 114–123. http://dx.doi.org/10.1016/j.tifs.2015.02.004

Liu, J., Feng, H., He, J., Chen, H., Ding, D., Luo, X., Dong, Q., Modeling wheat nutritional quality with a modified CERES-wheat model, European Journal of Agronomy (In Press) (2019). https://doi.org/10.1016/j.eja.2019.03.005

Liu, Z., Zhang, M., Bhandari, B., Wang, Y., 3D printing: Printing precision and application in food sector, Trends in Food Science & Technology 69 (2017) 83–94. http://dx.doi.org/10.1016/j.tifs.2017.08.018

López, L.A., Cadarso, M.A., Gómez, N., Tobarra, M.A., Food miles, carbon footprint and global value chains for Spanish agriculture: assessing the impact of a carbon border tax, Journal of Cleaner Production 103 (2015) 423–436. https://doi.org/10.1016/j.jclepro.2015.01.039

López-Avilés, A., Veldhius, A.J., Leach, M., Yang, A., Sustainable energy opportunities in localised food production and transportation: A case study of bread in the UK, Sustainable Production and Consumption 20 (2019) 98–116. https://doi.org/10.1016/j.spc.2019.05.004

Lopez-Quiroga, E., Wang, R., Gouseti, O., Fryer, P.J., Bakalis, S., Crystallisation in concentrated systems: A modelling approach, Food and Bioproducts Processing 100 (Part B) (2016) 525–534. https://doi.org/10.1016/j.fbp.2016.07.007

Luthra, S., Mangla, S.K., Yadav, G., An analysis of causal relationships among challenges impeding redistributed manufacturing in emerging economies, Journal of Cleaner Production 225 (2019) 949–962. https://doi.org/10.1016/j.jclepro.2019.04.011

Lv, Y., Lee, C., Wu, Z., Chan, H., Ip, W., Priority based distributed manufacturing process modeling via hierarchical timed colored petri net. IEEE Transactions on Industrial Informatics 9 (4) (2013) 1836-1846. https://doi.org/10.1109/TII.2012.2215043

MacCarthy, B., Brabazon, P.G., Bramham, J., Fundamental modes of operation for mass customization, International Journal of Production Economics 85 (2003) 289–304. https://doi.org/10.1016/S0925-5273(03)00117-8

McIntosh, R.I., Matthews, J., Mullineux, G., Medland, A.J., Late customisation: issues of mass customisation in the food industry, International Journal of Production Research 48 (2010) 1557–1574. https://doi.org/10.1080/00207540802577938

Mantoux, P., The Industrial Revolution in the Eighteenth Century: An outline of the beginnings of the modern factory system in England, (e-book) Methuen & Co LTD, London, 2013. ISBN: 978-1-136-58559-3

Marchant, J., Reuben, B., Alcock, J., Bear: A slice of history, The History Press, UK, 2008. ISBN 978-0-7524-47483.

Marcotte, E., Achieving particle size reduction with a multirow cage mill. Powder and Bulk Engineering Magazine – CSC publishing (2015) (accessed: 11/05/2017). http://www.powderbulk.com/enews/2015/whitepaper/stedman.pdf.

Market Business News. What is manufacturing? Definition and examples. (2019) https://marketbusinessnews.com/financial-glossary/manufacturing/ (accessed 03/01/2019)

Maroulis, Z.B., Saravacos, G.D., Food Plant Economics, Taylir & Francis Group/CRC Press, USA, 2008. ISBN: 978-0-8493-4021-5

Marquardt, D.W., An algorithm for least-squares estimation of nonlinear parameters, Journal of the Society for Industrial and Applied Mathematics 11 (2) (1963) 431–441. https://doi.org/10.1137 /0111030

Martin, M., Grossmann, I.E., BIOpt: A library of models for optimization of biofuel production processes, Computer Aided Chemical Engineering 30 (2012) 16–20. https://doi.org/10.1016/B978-0-444-59519-5.50004-6

Martín, M., Grossmann, I.E., Energy optimization of bioethanol production via gasification of switchgrass, AIChE Journal 57 (12) (2011) 3408–3428. https://doi.org/10.1002/aic.12544

Martin, M., Introduction to Software for Chemical Engineers, CRC Press/Taylor & Francis Group, USA, 2015. ISBN: 978-1-4665-9937-6

Martín, M., Martín, M., Cooling limitations in power plants: Optimal multiperiod design od natural draft cooling towers, Energy 135 (2017) 625–636. https://doi.org/10.1016/j.energy.2017.06.171

Martin, R, The Age of Customer Capitalism, Harvard Business Review, January-February (2010) 58–65. https://hbr.org/2010/01/the-age-of-customer-capitalism

Martín-Rodríguez, H., Cano, A., Marzopoulos, M., Improve engineering via whole-plant design optimization, Hydrocarbon Processing (December) (2010), 43–49.

Martins, M., Gastronomic tourism and the creative economy, Journal of Tourism, Heritage & Services Marketing 2 (2016) 33–37. http://doi.org/10.5281/zenodo.376346

Maslarić, M., Nikoličić, S., Mirčetić, D., Logistics Response to the Industry 4.0: the Physical Internet, Open Engineering 6 (2016) 511–517. https://doi.org/10.1515/eng-2016-0073

Matches. Index of process equipment (2014) (accessed 12/12/2017). http://www.matche.com/equipcost/EquipmentIndex.html

Mathisson, J., Chapter 6: Heat exchangers. In: Bylund, G. (ed.), Dairy processing handbook (3rd edition), Tetra Pak Processing Systems AB, Lund (Sweden), 2015. ISBN: 978-9-176-09719-9

MATLAB[a], Signal Processing Toolbox, Machine Learning and Deep Learning, (2019) [online] https://uk.mathworks.com/help/signal/ref/findchangepts.html?s_tid=doc_ta#responsive_offcanvas, accessed (24/06/2019)

MATLAB[b], Linear and Nonlinear Regression, Least-Squares Fitting, (2019) [online] https://uk.mathworks.com/help/curvefit/least-squares-fitting.html, accessed (25/06/2019)

Matt, D.T., Rauch, E., Dallasega, P., Trends towards Distributed Manufacturing Systems and modern forms for their design, Procedia CIRP 33 (2015) 185–190. https://doi.org/10.1016/j.procir.2015.06.034

Matthews, J., McIntosh, R., Mullineux, G., Contrasting opportunities for mass customisation in food manufacture and food processes. In: Fogliatto, F., da Silveira, G. (eds.) Mass Customization, Springer Series in Advanced Manufacturing, Springer, London, 2011. https://doi.org/10.1007/978-1-84996-489-0_17.

Matuda, T.G., Pessôa-Filho, P.A., Tadini, C.C., Experimental data and modeling of the thermodynamic properties of bread dough at refrigeration and freezing temperatures, Journal of Cereal Science 53 (2011) 126–132. https://doi.org/10.1016/j.jcs.2010.11.002

Maye, D., Ilbery, B., Regional Economies of Local Food Production: Tracing Food Chain Links Between 'Specialist' Producers and Intermediaries in the Scottish-English Border, European Urban and Regional Studies 13 (4) (2006) 337–354. https://doi.org/10.1177/0969776406068588

McAdams. W. H., Heat Transmission (2nd edition), McGraw-Hill Book Co. Inc., New York, 1942. ISBN 978-0-07-044799-8

McCabe, W.L., Smith, J.C., Harriott, P., Unit Operations of Chemical Engineering (5th ed.), McGraw-Hill Inc., Singapore, 1993. ISBN: 0-07-044844-2.

Mecklenburgh, J.C., Plant Layout: A Guide to the Layout of Process Plant and Sites, Leonard Hill Books, Aylesbury, 1973.

Mercasa, Últimos datos sobre el mercado del pan en España (2018) (accessed 14/01/2020) https://www.pastryrevolution.es/panaderia/el-mercado-del-pan-en-espana/

Migliore, G., Schifani, G., Cembalo, L., Opening the black box of food quality in the short supply chain: Effects of conventions of quality on consumer choice, Food Quality and Preference 39 (2015) 141–146 https://doi.org/10.1016/j.foodqual.2014.07.006

Miles, C.A., Van Beek, G., Veerkaamp, C.H.. Calculation of thermophysical properties of foods. In: Jowitt, R., Escher, F., Hallström, B., Meffert, H.F., Spiess, W.E.L. (eds.), Physical Properties of Foods, Applied Science Publishers, London, 1983. ISBN: 978-0-853-34213-7

Mingay, G.E., The Agricultural Revolution: Changes in Agriculture 1650–1880, Adam & Charles Black, London, 1977. ISBN: 978-0-71361-703-0

Minister of Agriculture and Agri-food Canada. Baby food trends in the United Kingdom (2012) (accessed: 12/25/2016) http://publications.gc.ca/collections/collection_2012/agr/A74-1-40-2012-eng.pdf

Mintel. World´s Market Intelligence Agency. UK sales of wet and dry baby food drop by 14% in 3 years as parents choose to make their own (2016) (accessed: 12/25/2016). http://www.mintel.com/press-centre/food-and-drink/uk-sales-of-wet-and-dry-baby-food-drop-by-14-in-3-years-as-parents-choose-to-make-their-own

Miranda, J., Ponce, P., Molina, A., Wright, P., Sensing, smart and sustainable technologies for Agri-Food 4.0, Computers in Industry 108 (2019) 21–36. https://doi.org/10.1016/j.compind.2019.02.002

Mitchell, A., Lafont, U., Hołyńska, M., Semprimoschnig C., Additive manufacturing — A review of 4D printing and future applications, Additive Manufacturing 24 (2018) 606–626. https://doi.org/10.1016/j.addma.2018.10.038

Mitsuishi, N., Miyari, Y., Heat transfer to non-Newtonian fluids in an agitated vessel. J. Chem. Eng. Japan 6 (1973) 415–420.

Miyawaki, O., Analysis and control of ice crystal structure in frozen food and their application to food processing, Food Science and Technology Research 7 (2001) 1–7, http://dx.doi.org/10.3136/ fstr.7.1

Mondal, A., Datta, A.K., Bread baking – A review, Journal of Food Engineering 86 (2008) 465–474. https://doi.org/10.1016/j.jfoodeng.2007.11.014

Monteau, J.Y., Purlis, E., Besbes, E., Jury, V., Le-Bail, A., Water transfer in bread during staling: Physical phenomena and modelling, Journal of Food Engineering 211 (2017) 95–103. https://doi.org/10.1016/j.jfoodeng.2017.04.016

Moragues-Faus, A., Carroll, B., Reshaping urban political ecologies: an analysis of policy trajectories to deliver food security. Food Security 10 (6) (2018) 1337–1351. http://dx.doi.org/10.1007/s12571-018-0855-7

Morini G.L., Viscous Dissipation. In: Li D. (eds.) Encyclopedia of Microfluidics and Nanofluidics, Springer, Boston, 2013

Morrisons (2019) (accessed 30/09/2019) https://groceries.morrisons.com

Motard, R.L., Shacham, M., Rosen, E.M., Steady state chemical process simulation, AIChE Journal 21 (3) (1975) 417–436. https://doi.org/10.1002/aic.690210302

Mourtzis, D, Doukas, M., Decentralized manufacturing systems review: challenges and outlook, Logistic Research 5 (2012) 113-121. https://doi.org/10.1007/s12159-012-0085-x

Muhuri, P.K., Shukla, A.K., Abraham, A., Industry 4.0: A bibliometric analysis and detailed overview, Engineering Applications of Artificial Intelligence 78 (2019) 218–235. https://doi.org/10.1016/j.engappai.2018.11.007

Mundler, P., Criner, G., Food Systems: Food Miles, Encyclopedia of Food and Health (2016) 77–82. https://doi.org/10.1016/B978-0-12-384947-2.00325-1

Nagpal, A., Lei, J., Khare, A., To choose or to reject: the effect of decision frame on food customization decisions, Journal of Retailing 91 (2015) 422–435. https://doi.org/10.1016/j.jretai.2014.12.001

Nakamura, E., Pass-through in retail and wholesale, Am. Econ. Rev. 98 (2) (2008), 430–37. https://doi.org/10.3386/w13965.

Nestlé, M., Food Politics: How the Food Industry Influences Nutrition and Health, University of California Press Ltd, London, England, 2002. ISBN:0-520-22465-5

Newnan, D.G., Eschenbach, T.G., Lavella, J.P., Engineering Economic Analysis (9th ed.), Oxford University Press Inc., New York, 2004. ISBN 0-19-516807-0.

Niziolek, AM, Onel, O and Floudas, CA, Production of benzene, toluene, and xylenes from natural gas via methanol: process synthesis and global optimization, AIChE Journal 62 (2016) 1531–1556. https://doi.org/10.1002/aic.15144

Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D., Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Composites Part B: Engineering 143 (2018) 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Noseworthy, B.L., Williams, P.L., Blum, I., MacLeod, M., The Availability and Relative Cost of Locally Produced Foods in Grocery Stores in Nova Scotia, Journal of Hunger & Environmental Nutrition 6 (2011) 188–206. https://doi.org/10.1080/ 19320248.2011.576594

Ocon, J., Tojo, G., Problemas de Ingenieria Química: Operaciones básicas. Aguilar S.A., Madrid, 1980. ISBN 978-8-40-320105-7

ONS, Office for National Statistic, UK manufacturers' sales by product (1052 - Manufacture of ice cream). https://www.ons.gov.uk/businessindustryandtrade/manufacturingandproductionindustry/datasets/ukmanufacturerssalesbyproductprodcom

Ovando-Martinez, M., Whitney, K., Reuhs, B.L., Doehlert, D.C., Simsek, S., Effect of hydrothermal treatment on physicochemical and digestibility properties of oat starch, Food Res. Int. 52 (2013) 17–25. https://doi.org/10.1016/j.foodres.2013.02.035

Owen, M.S., Thermal Properties of Foods (Chapter 9). In: ASHRAE Handbook Refrigeration, Inch-Pound Edition, 2006. ISBN 1-931862-86-9

Ozcan-Deniz, G., Zhu, Y., Multi-objective optimization of greenhouse gas emissions in highway construction projects, Sustainable cities and Society 28 (2017) 162–171. https://doi.org/10.1016/j.scs.2016.09.009

Paton, J., Khatir, Z., Thomson, H., Kapur, N., Toropov, V., Thermal energy management in the bread baking industry using a system modelling approach, Applied Thermal Engineering 53 (2) (2013) 340–347. https://doi.org/10.1016/j.applthermaleng.2012.03.036

Paul O. Abbe. Ribbon Blenders, design, capacities and dimensions (2017) (accessed 7/15/2017) http://www.pauloabbe.com/images/pauloabbe_ribbon-blender-capacity.pdf.

Payscale, Salary Data & Career Research Centre (2017) (accessed 02/10/2017). http://www.payscale.com/research/UK/Country=United_Kingdom/Salary.

Peters, M. S., Timmerhaus, K. D., Plant Design and Economics for Chemical Engineers, fifth ed., McGraw-Hill, Singapore, 2003. ISBN: 0-07-049613-7.

Petzold, G., Aguilera, J.M., Ice morphology: fundamentals and technological applications in foods, Food Biophysics 4 (2009) 378–396. http://dx.doi.org/10.1007/s11483-009-9136-5

Pieniak, Z., Verbeke, W., Vanhonacker, F., Guerrero, L., Hersleth, M., Association between traditional food consumption and motives for food choice in six European countries, Appetite 53 (1) (2009) 101–108. https://doi.org/10.1016/j.appet.2009.05.019

Pine, B.J, Mass Customization. The New Frontier in Business Competition. Harvard Business School Press, Boston, 1993. ISBN: 0-87584-373-7

Pinedo, M.L., Scheduling. Theory, Algorithms, and Systems (5th ed.), Springer, New York, 2016. https://www.doi.org/10.1007/978-3-319-26580-3 Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso: Food security and food production systems. In: Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US , 2014 pp. 485-533.

Probake, Bakery equipment specialists – conical rounder (2019) (accessed 28/10/2019) https://probake.com/equipment/bread-equipment/conical-rounder/

Process Systems Enterprise, Advanced Process Modelling examples (2019) [online] https://www.psenterprise.com/concepts/examples, accessed (24/06/2019)

Pullman, M., Wikoff, R., Institutional sustainable purchasing priorities: Stakeholder perceptions vs environmental reality, International Journal of Operations & Production Management 37 (2017) 162–181. https://doi.org/10.1108/IJOPM-07-2014-0348

Purlis, E., Bread baking: Technological considerations based on process modelling and simulation, Journal of Food Engineering 103 (2011) 92–102. https://doi.org/10.1016/j.jfoodeng.2010.10.003

Pyler, E.J., Gorton, L.A., Baking Science & Technology: Formulation and Production: Volume 2, (4th edition), Sosland Pub Co, USA, 2010. ISBN: 978-0-982-02391-4

P&G. Policies & Practices. Purpose, Values & Principles (2020) (accessed: 16/06/2020). https://us.pg.com/policies-and-practices/purpose-values-and-principles/

Qi, Y., Tang, M., Zhang, M., Mass Customization in Flat Organization: The Mediating Role of Supply Chain Planning and Corporation Coordination, Journal of Applied Research and Technology 12 (2014) 171–181. https://doi.org/10.1016/S1665-6423(14)72333-8

Qin, F., Chen, X.D., Ramachandra, S., Free, K., Heat transfer and power consumption in a scraped-surface heat exchanger while freezing aqueous solutions, Separation and Purification Technology 48 (2006) 150–158. https://doi.org/10.1016/j.seppur.2005.07.018

Radatz, H., Elischewski, J.M., Heitmann, M., Schembecker, G., Bramsiepe, C., Design of equipment modules for flexibility, Chemical Engineering Science 168 (2017) 271–288. http://dx.doi.org/10.1016/j.ces.2017.04.021

Ramli, W., Daud, W., Drum Dryers, in: A.S. Mujumdar (Ed.), Handbook of Industrial Drying, Chapman and Hall/CRC, 2014, pp. 249–257.

Rauch, E., Dallasega, P., Matt, D.T., Distributed manufacturing network models of smart and agile mini-factories, Int. J. Agile Systems and Management 10 (2017) 185–205. https://doi.org/10.1504/IJASM.2017.088534

Rauch, E., Dallasega, P., Matt, D.T., Sustainable production in emerging markets through distributed manufacturing systems (DMS). J. Clean. Prod. 135 (2016) 127–138. http://dx.doi.org/10.1016/j.jclepro.2016.06.106

Rauch, E., Dallasega, P., Matt, D.T., Sustainable production in emerging markets through Distributed Manufacturing Systems (DMS), J. Clean. Prod. 135 (2016) 127–138. https://doi.org/10.1016/j.jclepro.2016.06.106

Rauch, E., Dallinger, M., Dallasega, Matt, D.T., Sustainability in Manufacturing through Distributed Manufacturing Systems (DMS), Procedia CIRP 29 (2015) 544-549. https://doi.org/10.1016/j.procir.2015.01.069

Ravimannan, N., Sevvel, P., Saarutharshan, S., Study on fungi associated with spoilage of bread, Int. J. Adv. Res. Biol. Sci. 3 (4) (2016) 165–167. http://s-o-i.org/1.15/ijarbs-2016-3-4-23

Reay, D., Ramshaw, C., Harvey, A., Chapter 2 - Process Intensification – An Overview. In: Reay, D., Ramshaw, C., Harvey, A. (eds) Process Intensification. Engineering for Efficiency, Sustainability and Flexibility (2nd edition) Butterworth-Heinemann, Oxford, 2013. https://doi.org/10.1016/B978-0-08-098304-2.00002-X

Reay, D., Ramshaw, C., Harvey, A., Chapter 2 - Process Intensification – An Overview. In: Reay, D., Ramshaw, C., Harvey, A. (eds) Process Intensification. Engineering for Efficiency, Sustainability and Flexibility (2nd edition) Butterworth-Heinemann, Oxford, 2013. https://doi.org/10.1016/B978-0-08-098304-2.00002-X

Reed, G., Nagodawithana, T.W., Yeast Technology, Springer, Dordrecht, 1990. https://doi.org/10.1007/978-94-011-9771-7

Reh, C., Bhat, S.N., Berrut, S., Determination of water content in powdered milk, Food Chem. 86 (2004) 457–464. https://doi.org/10.1016/j.foodchem.2003.10.028.

Renaud, T., Briery, P., Andrieu, J., & Laurent, M., Thermal properties of model foods in the frozen state, Journal of Food Engineering 15 (1992) 83–97. https://doi.org/10.1016/0260-8774(92)90027-4

Ritchie, H., Roser, M., Environmental impacts of food production (2020) (accessed 02/07/2020) https://ourworldindata.org/environmental-impacts-of-food

Ritterm M., Schanz, H., The sharing economy: A comprehensive business model framework, Journal of Cleaner Production 213 (2019) 320–331. https://doi.org/10.1016/j.jclepro.2018.12.154

Rodman, A.D., Gerogiorgis, D.I., Multi-objective process optimisation of beer fermentation via dynamic simulation, Food and Bioproducts Processing 100 (Part A) (2016) 255–274. https://doi.org/10.1016/j.fbp.2016.04.002

Rohmer, S.U.K., Gerdessen, J.C., Claassen, G.D.H. Sustainable supply chain design in the food system with dietary considerations: A multi-objective analysis, European Journal of Operational Research 273 (3) (2019) 1149–1164. https://doi.org/10.1016/j.ejor.2018.09.006

Roos Y.H., Fryer P.J., Knorr D., Schuchmann P., Schröen K., Schutyser M.A.I., Trystram G., Windhab E.J. Food engineering at multiple scales: case studies, challenges and the future – a European perspective, Food Engineering Reviews 8 (2016) 91–115. https://doi.org/10.1007/s12393-015-9125-z

Ruffo, M., Tuck, C., Hague, R., Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes, Proceedings IMechE Part B: J. Engineering Manufacture 220 (6) (2006) 1417–1427, https://doi.org/10.1243/09544054JEM517

Russel, A.B., Cheney, P.E., Wantling, S.D., Influence of freezing conditions on ice crystallisation in ice cream, Journal of Food Engineering 39 (1999) 179–191. https://doi.org/10.1016/S0260-8774(98)00161-7

Sage, C., Social embeddedness and relations of regard: alternative ‘good food’ networks in South-West Ireland. J. Rural Stud. 10 (2003) 47–60. http://dx.doi.org/10.1016/S0743-0167(02)00044-X

Sainsburys (2019) (accessed 30/09/2019) https://www.sainsburys.co.uk

Salim, I.C., Almeida-García, F., González-García, S., Romero-Rodríguez, A., Ruíz-Nogueiras, B., Pereira-Lorenzo, S., Feijoo, G., Moreira, M.T., Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain, Science of The Total Environment (In press) (2020). https://doi.org/10.1016/j.scitotenv.2020.136720

Samsung, Cooking Appliance – Gas Oven NX58H5600SS (2019) (accessed 30/12/2019) https://www.samsung.com/ca/cooking-appliances/gas-range-nx58h5600ss/

Sánchez, A., Martín, M., Scale up and scale down issues of renewable ammonia plants: Towards modular design. Sustainable Production and Consumption 16 (2018) 176–192. https://doi.org/10.1016/j.spc.2018.08.001

Scanico, Spiral systems for food processing – spiral proofer (2019) (accessed 28/10/2019) http://scanico.com/our-products/spiral-proofer/

Schenk, O., Wächter, A., Hagemann, M., Matching-based preprocessing algorithms to the solution of saddle-point problems in large-scale nonconvex interior-point optimization, Computational Optimization and Applications 36 (2007) 321–341. https://doi.org/10.1007/s10589-006-9003-y

Schmenner, R.W., Looking ahead by looking back: Swift, even flow in the history of manufacturing, Production and Operation Management 10 (2001) 87–96. https://doi.org/10.1111/j.1937-5956.2001.tb00069.x

Schulz. Brewing Equipment, 2019. https://schulz-brewery.com/en/ (accessed 12/06/2019)

Schwartz, J.B., Optimization techniques in product formulation, Journal of the Society of Cosmetic Chemists 32 (5) (1981) 287–301.

Schwartzberg, H.C., Food Freeze Concentration. In: Schwartzberg, H.G., Rao, M.A., Biotechnology and Food Process Engineering (eds), Marcel Dekker, New York, 1990. ISBN: 0-8247-8363-8.

Schiess, S., Grote, V., Scaglioni, S., Luque, V., Martin, F., Stolarczyk, A., Vecchi, F., Koletzko, B., Introduction of complementary feeding in 5 European countries, Journal of Pediatric Gastroenterology and Nutrition 50 (2010) 92–98. https://doi.org/10.1097/MPG.0b013e31819f1ddc

Scottish Government, Scottish Dairy Supply Chain Greenhouse Gas Emissions: Main Project Report (2011) (accessed 30/09/2019) http://www.gov.scot/Publications/2011/02/22152837/0

Sellitto, M.A., Vial, L.A.M., Viegas, C.V., Critical success factors in short food supply chains: case studies with milk and dairy producers from Italy and Brazil, J. Clean. Prod. 170 (2018) 1361–1368. https://doi.org/10.1016/j.jclepro.2017.09.235.

Severini, C., Derossi, A., Could the 3D Printing Technology be a Useful Strategy to Obtain Customized Nutrition?, Journal of Clinical Gastroenterology 50 (2016) 175–178. https://doi.org/10.1097/MCG.0000000000000705

Shah, P., Campbell, G.M., Dale, C. and Rudder, A., Modelling bubble growth during proving of bread dough: predicting the output from chop in rheofermentometer. In: Campbell, G.M., Webb, C., Pandiella, S.S., and Niranjan, K. (eds.), Bubbles in Food, American Association of Cereal Chemists, Manchester, 1999. ISBN: 978-1-891-12708-3

Shao, J., Ünal, E., What do consumers value more in green purchasing? Assessing the sustainability practices from demand side of business. Journal of Cleaner Production 209 (2019) 1473 – 1483. https://doi.org/10.1016/j.jclepro.2018.11.022

Sieniutycz, S., Jeżowski, J., Heat integration within process integration. Energy Optimization in Process Systems and Fuel Cells (2nd ed.), Elsevier, 2013. https://doi.org/10.1016/B978-0-08-098221-2.00012-6

Sikhwal, R.K., Childs, P.R.N., Identification of Optimised Open Platform Architecture Products for Design for Mass Individualisation. In: Chakrabarti, A. (eds), Research into Design for a Connected World. Smart Innovation, Systems and Technologies 135. Springer, Singapore, 2019. https://doi.org/10.1007/978-981-13-5977-4_72

Silla, H., Chemical Process Engineering, Design and Economics, Marcel. Dekker Inc., New York, 2003. https://doi.org/10.1201/9780203912454

Sims, R., Flammini, A., Puri, M, Bracco, S., Opportunities for Agri-Food Chains to Become Energy-Smart, FAO and USAID, 2015. ISBN 978-92-5-108959-0

Sinnot, K, Chemical Engineering Design (4th ed.), Elsevier Butterworth-Heinemann, London, 2005. ISBN: 0-7506-6538-6.

Sinnott, R.K., Towler, G., Chemical Engineering Design. Principles, Practice and Economics of Plant and Process Design, second ed., Elsevier, Singapore, 2013. ISBN:978-0-08-096659-5

Sirasitthichoke, C., Armenante, P.M., Power Dissipation and Power Number Correlations for a Retreat-Blade Impeller under Different Baffling Conditions, Ind. Eng. Chem. Res. 56 (2017) 10123−10133. https://doi.org/10.1021/acs.iecr.7b02634

Skeat, W.W., An etymological dictionary of the English language. Clarendon Press, Oxford, 1882. ISBN: 978-0-399-50049-7

Skelland, A.H.P., Correlation of scraped-film heat transfer in the rotator, Chem. Eng. Sci. (7) (1958) 166–175.

Sloan, P., Record-breaking ice cream sales mean scorching new flavours – and here's how to serve them at home (2018). https://www.telegraph.co.uk/food-and-drink/news/record-breaking-ice-cream-sales-mean-scorching-new-flavours/

Smith, G.D., Numerical solution of partial differential equations (3rd ed.), Clarendon Press, Oxford, 1985. ISBN: 0-19-859650-2.

Spring, M, Dalrymple, J.F., Product customisation and manufacturing strategy, International Journal of Operations & Product Management 20 (4) (2000) 441–467, https://doi.org/10.1108/01443570010314782

Srai[a], 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, Distributed manufacturing: scope, challenges and opportunities. Int. J. Prod. Res. 54 (2016) 6917–6935. https://doi.org/10.1080/00207543.2016.1192302

Srai,[b] J.S., Harrington, T.S., Tiwari, M.K., 2016. Characteristics of redistributed manufacturing systems: A comparative study of emerging industry supply networks. International Journal of Production Research 54 (23), 6936–6955. https://doi.org/10.1080/00207543.2016.1214765

Stanford, J., The resurgence of gig work: Historical and theoretical perspectives, Economic and Labour Relations Review 28 (3) (2017) 382–401. https://doi.org/10.1177/1035304617724303

Stear, C.A., Aims and Requirements of the Baking Process. In: Stear, C.A. (ed.) Handbook of Breadmaking Technology, Elsevier Science Publishers LTD, Essex, 1990. https://doi.org/10.1007/978-1-4615-2375-8_15

Stearns, P.N., The Industrial Revolution in World History, (3rd ed.), Westview Press, Cambrige, 2007. ISBN:978-0-813-4360-0

Stedman. H Series Impact Mills Catalogue (2017) (accessed 7/15/2017). http://www.stedman-machine.com/docs/H-Series-Cage-Mill.pdf

Sun, J., Zhou, W., Huang, D., Fuh, J.Y.H., Hong, G.S., An Overview of 3D printing Technologies for food fabrication, Food and Bioprocess Technology 8 (8) (2015) 1605–1615. https://doi.org/10.1007/s11947-015-1528-6

Sutherland, J.W., Richter, J.S, Hutchins, M.J., Dornfeld, D., Dzombak, R., Mangold, J., Robinson, S., Hauschild , M.Z., Bonoue, A., Schönsleben, P., Friemann, F., The role of manufacturing in affecting the social dimension of sustainability, CIRP Annals – Manufacturing Technology 65 (2016) 689–712. https://doi.org/10.1016/j.cirp.2016.05.003

Sutherland, W., Jarrahi, M.H., The sharing economy and digital platforms: A review and research agenda, International Journal of Information Management 43 (2018) 328–341. https://doi.org/10.1016/j.ijinfomgt.2018.07.004

Sveba Dahlen, Professional baking equipment (2019) (accessed 30/12/2019) https://sveba.com/en/products

Tapasya Engineering Works, Double Cone Blender (2017) (accessed 7/15/2017). http://www.tapasyaindia.net/pdfs/Double%20Cone%20Blender.pdf

Tapper, J., A 99 sprinkles and no diesel: here come the electric ice-cream vans (2019) (accessed 30/09/2019) https://www.theguardian.com/environment/2019/jun/02/ice-cream-vans-poised-to-go-electric-diesel-pollution

Tassou, S.A., Hadeaway, A., Marriot, D., 2008. Greenhouse Gas Impacts of Food Retailing. DEFRA, London. Report F0405 for Defra.

Tassou, S.A., Kolokotroni, M., Gowreesunker, B., Stojceska, V., Azapagic, A., Fryer, P., Bakalis, S., Energy demand and reduction opportunities in the UK food chain. P. I. Civil Eng.-Energy 167 (2014) 162–170. https://doi.org/10.1680/ener.14.00014

Taylor, A.J., 11 - Measurement and simulation of flavour release from foods, In: McClements, D.J., Decker, E.A. (eds), Designing Functional Foods. Measuring and Controlling Food Structure Breakdown and Nutrient Absorption, Woodhead Publishing Limited, Cambridge, 2009. https://doi.org/10.1533/9781845696603.2.294

Telegraph Travel, Britain's best ice cream parlours (2018) (accessed 30/09/2019) https://www.telegraph.co.uk/travel/destinations/europe/united-kingdom/articles/britains-best-ice-cream-parlours/

Tesco (2019) (accessed 30/09/2019) http://www.tesco.com

Tharp, B.W., Young, L.S., Tharp & Young on Ice Cream. An Encyclopedic Guide to Ice Cream Science and Technology, DEStech Publications Inc., Pennsylvania, 2013. ISBN 978-1-932-07868-8.

The Carbon Trust, Improving the efficiency of bakery ovens. A case study (2015) (accessed: 05/12/2018). https://www.carbontrust.com/media/642185/cts402-improving-efficiency-of-bakery-ovens.pdf.

The Henry Group, Baking equipment – bakery Spiral Coolers (2019) (accessed 04/11/2019) www.thehenrygroup.com/spiral-coolers.html

The Quaker Oats Company. Process for preparing an instant baby cereal porridge product. Chicago, United States Patent (1984). Inventors: S. Gantwerker, S. Leong. US 4,485,120. 11/27/1984.

Therdthai, N., Zhou, W., Adamczak, T., Optimisation of the temperature profile in bread baking, Journal of Food Engineering 55 (2002) 41–48. https://doi.org/10.1016/ S0260-8774(01)00240-0

Toler, S., Briggeman, B.C., Lusk, J.L., Adams, D.C., Fairness, Farmers Markets, and Local Production, American Journal of Agricultural Economics 91 (2009) 1272–1278. https://doi.org/10.1111/j.1467-8276.2009.01296.x

Toussaint-Samat, M., A History of Food (2nd edition), John Wiley & Sons, Chichester, United Kingdom, 2009. ISBN: 978-1-405-18119-8

Tsarouhas, P.H., Arvanitoyannis, I.S., Reliability and Maintainability Analysis of Bread Production Line, Critical Reviews in Food Science and Nutrition 50 (2010) 327–343. https://doi.org/10.1080/10408390802544488

Tsarouhas, P.H., Classification and calculation of primary failure modes in bread production line, Reliability Engineering & System Safety 94 (2) (2009) 551–557. https://doi.org/10.1016/j.ress.2008.06.014

Tseng, M.M., Hu, S.J., Mass Customization, in: Laperrière, L., Reinhart, G. (Eds.), The International Academy for Production Engineering, CIRP Encyclopedia of Production Engineering. Springer–Heidelberg, Berlin, 2014, pp. 836–843. ISBN 978-3-642-20616-0

Tseng, M.M., Jiao, J., Mass customization. In: Salvendy G (ed) Handbook of industrial engineering: technology and operations management. Wiley, New York, 2001. 684–709. ISBN: 0471-33057-4.

Tso, W.W., Niziolek, A.M., Onel, O., Demirhan, C.D., Floudas, C.A., Pistikopoulos, E.N., Reprint of: Enhancing natural gas-to-liquids (GTL) processes through chemical looping for syngas production: Process synthesis and global optimization, Computers & Chemical Engineering 116 (2018) 521–538. https://doi.org/10.1016/j.compchemeng.2018.10.017

Tutu, B.O., Anfu, P.O., Evaluation of the food safety and quality management systems of the cottage food manufacturing industry in Ghana, Food Control 101 (2019) 24–28. https://doi.org/10.1016/j.foodcont.2019.02.028

U.S. Department of Health and Human Services, Grade “A” pasteurised milk ordinance, Food and Drug Administration, College Park (Maryland - USA), 2017.

UK Statutory Instruments, The Dairy Products (Hygiene) Regulations 1995. http://www.legislation.gov.uk/uksi/1995/1086/made

UNESCO, Intangible Cultural Heritage. Traditional Mexican cuisine, (2010), accessed (31/05/2019)

https://ich.unesco.org/en/RL/traditional-mexican-cuisine-ancestral-ongoing-community-culture-the-michoacan-paradigm-00400

USDA. United States Department of Agriculture. FoodData Central 2020, accessed (06/07/2020) https://fdc.nal.usda.gov/

Vanderbei, R.J., An Interior-Point Algorithm for Nonconvex Nonlinear Programming, Computational Optimization and Applications 13 (1999) 231–252. https://doi.org/10.1023/A:1008677427361

Vanin, F.M., Lucas, T., Trystram, G., Crust formation and its role during bread baking, Trends in Food Science & Technology 20 (2009) 333–343. https://doi.org/10.1016/j.tifs.2009.04.001

VanWees, S.R., Hartel, R.W., Microstructure of Ice Cream and Frozen Dairy Desserts (Chapter 10). In: El-Bakry, M.M.A-R., Sanchez, A., Mehta, B.M., Microstructure of Dairy Products, John Wiley & Sons Ltd, UK, 2018. https://doi.org/10.1002/9781118964194.ch10

VanWees, S.R., Rankin, S.A., Hartel, R.W., The microstructural, melting, rheological, and sensorial properties of high overrun frozen desserts, Journal of Texture Studies (2019) 1–9. https://doi.org/10.1111/jtxs.12461

Vasquez-Nicholson, J., Phillips, S., United Kingdom Retail Foods Report 2018, USDA GAIN reports, 15/06/2018. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Retail%20Foods_London_United%20Kingdom_6-15-2018.pdf

Verdú, S., Barat, J.M., Grau, R., Improving bread-making processing phases of fibre-rich formulas using chia (Salvia hispanica) seed flour, LWT - Food Science and Technology 84 (2017) 419–425. https://doi.org/10.1016/j.lwt.2017.06.007

Villacís, S., Martínez, J., Riofrío, A. J., Carrión, D. F., Orozco, M. A., Vaca, D., Energy efficiency analysis of different materials for cookware commonly used in induction cookers, Energy Procedia 75 (2015) 925 – 930. https://doi.org/10.1016/j.egypro.2015.07.252

Walas, S.M., Chemical Process Equipment: Selection and Design, third ed., Butterworth-Heinemann, United States, 1990. ISBN 0-7506-9385-l.

Waltz, R.A., Morales, J.L., Nocedal, J., Orban, D., An interior algorithm for nonlinear optimization that combines line search and trust region steps, Mathematical Programming 107 (2006) 391–408. https://doi.org/10.1007/s10107-004-0560-5

Wang, B, The Future of Manufacturing: A New Perspective, Engineering 4 (2018) 722–728. https://doi.org/10.1016/j.eng.2018.07.020

Wang, S., Ab initio bread design: The role of bubbles in doughs and pores in breads, Technical report (PhD thesis) at The University of Western Australia, 2015.

Wang, S., Sun, Y., Wang, J., Wang, S., Copeland, L., Molecular disassembly of rice and lotus starches during thermal processing and its effect on starch digestibility, Food Function 7 (2016) 1188–1195. https://doi.org/10.1039/c6fo00067c

Wang S., Wan J., Zhang D., Li D., Zhang C, Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination, Computer Networks 101 (2016) 158–168. https://doi.org/10.1016/j.comnet.2015.12.017

Wang, Y., Bu, G., Geng, X., Zhu, Z., Cui, P., Liao, Z., Design optimization and operating pressure effects in the separation of acetonitrile/methanol/water mixture by ternary extractive distillation, Journal of Cleaner Production 218 (2019) 212–224. https://doi.org/10.1016/j.jclepro. 2019.01.324

Warren, M.M., Hartel, R.W., Structural, Compositional, and Sensorial Properties of United States Commercial Ice Cream Products, Journal of Food Science 79 (10) (2014) 2005 – 2013. https://doi .org/10.1111/1750-3841.12592

Weaver, C.M., Dwyer, J., Fulgoni III, V.L., King, J.C., Leveille, G.A., MacDonald, R.S., Ordovas, J., Schnakenberg, D., Processed foods: contributions to nutrition, The American Journal of Clinical Nutrition 99 (2014) 1525–1542. https://doi.org/10.3945/ajcn.114.089284

Webber, V., de Carvalho, S.M., Ogliari, P.J., Hayashi, L., Barreto, P.L.M., Optimization of the extraction of carrageenan from Kappaphycus alvarezii using response surface methodology, Ciência e Tecnologia de Alimentos 32 (4) 812 – 818. https://doi.org/10.1590/S0101-20612012005000111

Welch, R.W., Mitchell, P.C., Food processing: a century of change, British Medical Bulletin 56 (1) (2000) 1–17. https://doi.org/10.1258/0007142001902923

Wiendahl, H.P., El Maraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.H., Duffie, N., Brieke, M., Changeable Manufacturing - Classification, Design and Operation, CIRP Annals 56 (2007) 783–809. https://doi.org/10.1016/j.cirp.2007.10.003

Williams, L., Start your own ice-cream business (2012) (accessed 30/09/2019) https://www.dairyscience.info/index.php/ice-cream/218-ice-cream-startup.html

Williamson, M.E., Wilson, D.I., Development of an improved heating system for industrial tunnel baking ovens, Journal of Food Engineering 91 (1) (2009) 64–71. https://doi.org/10.1016/j.jfoodeng.2008.08.004

Wilson, A.I., Large-Scale Manufacturing, Standardization, and Trade. In: Oleson, J.P. (ed.) The Oxford Handbook of Engineering and Technology in the Classical World, Oxford University Press Inc., New York, 2009. https://doi.org/10.1093/oxfordhb/9780199734856.013.0016

Windt K. (2014) Distributed Manufacturing. In: The International Academy for Production Engineering, Laperrière L., Reinhart G. (eds), CIRP Encyclopedia of Production Engineering. Springer, Berlin, 2014. https://doi.org/10.1007/978-3-642-20617-7

Wittbrodt, B.T., Glover, A.G., Laureto, J., Anzalone, G.C., Oppliger, D., Irwin, J.L., Pearce, J.M., Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers, Mechatronics 23 (2013) 713–726. http://dx.doi.org/10.1016/j.mechatronics.2013.06.002

Wrangham, R., Catching fire: how cooking made us human, Profile Books, London, 2009. ISBN: 978-1-84668-286-5

Zamarripa, M.A., Aguirre, A.M., Méndez, C.A., Espuña, A., Mathematical programming and fame theory optimization-based tool for supply chain planning in cooperative/competitive environments, Chemical Engineering Research and Design 91 (2013) 1588–1600. https://doi.org/10.1016/j.cherd.2013.06.008

Zhang, L., Doursat, C., Vanin, F.M., Flick, D., Lucas, T., Water loss and crust formation during bread baking, Part I: Interpretation aided by mathematical models with highlights on the role of local porosity, Drying Technology 35 (2017) 1506–1517. https://doi.org/10.1080/07373937.2016.1260029

Zhou, P., Finite Difference Method. In: Zhou, P. (ed), Numerical Analysis of Electromagnetic Fields. Springer, Berlin, 1993. https://doi.org/10.1007/978-3-642-50319-1_3

Zhou, W., Hui, Y.H., Bakery Products Science and Technology (2nd ed.), John Wiley & Sons West Sussex (UK), 2014. ISBN 978-1-119-96715-6

Zipkin, P., The Limits of Mass Customization, MIT Sloan Management Review 42 (3) (2001) 81–87.

Zore, Z., Čuček, L., Širovnik, D., Pintarič, Z.N., Kravanja, Z., Maximizing the sustainability net present value of renewable energy supply networks, Chemical Engineering Research and Design 131 (2018) 245–265. https://doi.org/10.1016/j.cherd.2018.01.035

Žukauskas, A., Enhancement of forced convection heat transfer in viscous fluid flows, International Journal of Heat and Mass Transfer 37 (1994) 207–212. https://doi.org/10.1016/0017-9310(94)90022-1

Zuñiga, R., Le-Bail, A., Assessment of thermal conductivity as a function of porosity in bread dough during proving, Food and Bioproducts Processing 87 (2009) 17–22. https://doi.org/10.1016/j.fbp.2008.04.002

Appendix A

Supplementary material for Chapter 3

The following appendix has been published in *Sustainable Production and Consumption*, Volume 19 (Almena et al., 2019a), as supplementary material

A.1. Unit Cost Correlations.

Table A.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: $C_b(\$_{2014}) = 11.20\,\dot{V} + 213{,}015$ Pressure 150 to 600 psi: $C_b(\$_{2014}) = 22.02\,\dot{V} + 474{,}139$ Pressure 600 to 1500 psi: $C_b(\$_{2014}) = 25.21\,\dot{V} + 621{,}581$	S8 S9 S10
Vertical Vessel –Silos and Intermediate tank–	$C_v(\$_{2014}) = 231.50\,W^{0.61}$	S11
Marshall and Swift Cost Index (IM&S)	$IM\&S_{\,year} = 51.39\,year - 101{,}795$ $C_{MSCI}(\$_{2016}) = C_{MSCI}(\$_{2014})\dfrac{IM\&S_{\,2016}}{IM\&S_{\,2014}}$	S12 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.

A.2. Artisanal and Industrial Process Equipment.

Table A.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 A.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}

A.3. Double Drum Dryer modelling and optimisation.

An algorithm has been implemented to choose the cheapest double drum dryer (DDD) model from a commercial catalogue (see Table A.3) that meets the heat supply requirements and operates using the lowest energy for each selected plant throughput. Each model within the catalogue is characterised by its specific dimensions (diameter and length), operating rotational speed range and power consumption. Section B.5 in Appendix B thoroughly describe the mathematical model for this equipment, that is summarised here in Table A.4.

The optimisation routine is, however, explained in the following lines. An objective function (J_{DD} from table A.4) is designed to minimise the differences between (a) the target moisture content set by mass balances and the one given by each DDD model, (b) the evaporated water flow in the mass balances and the one given by the DDD, and (c) the heat requirements computed in the energy balances and the heat supply needed for each DDD from the catalogue. Table A.5 shows the design variables and the operating range assumed for them. Diameter (d_0) and length (L) are the discrete variables associated to each DDD model, the drying heat (Q_{dry}) computed at the energy balance is a continuous variable that depends on the throughput studied, and are the design variables constrained to the operating conditions set by the manufacturer for each DDD model.

The optimization will be achieved by the Matlab function "*fmincon*". The values of the design variables that minimises J_{DD} is therefore found for each DDD model within the catalogue. To obtain a global minimum and overcome a possible non-convexity, a multi-shot of initial steps, i.e. a line space array of initial conditions values inside the lower and upper bound range, is set. If the multi-shot gives different solutions, its minimum is selected as the final result.

Table A.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)*
$$\dot{m}_w{}^f = {\left(Q_{drum} - Q_{sensible\ gel}\right)}/{\Delta H_{vap}{}^{H_2O}}$$
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 A.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 difference Heat supply-needed	$\sqrt{\left(\frac{N_{DDD} * Q_{Drum} - Q_{dry}}{Q_{dry}}\right)^2} < 1$

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

The optimization routine is carried out for each double drum dryer model found in the catalogue, and for a combination of dryers of the same model from 1 to 10 numbers of units (the feed stream is divided among the number of dryers considered). A feasible choice is constrained to a difference below 1% between Q_{drum} (heat supplied by the combination of DDD) and Q_{dry}. A big M method is implemented to penalise choices that return higher values. The steam required at the temperature set by the optimisation is produced on a boiler, whose price is relevant enough for the economics. The cost of the couple dryer-boiler is therefore included on the model's decision making. Using the cost correlations compiled in Table A.1, the cost of both equipment can be computed. The final decision comprises the cheapest combination of dryer (previously optimised) and boiler. The solutions given by this stage of the sequential model are the double drum dryer selected, the number of DDD units, the operation conditions (steam temperature, steam flow, rotary velocity), the power consumption and the cost of both dryer and boiler.

A.4. Heat transfer modelling in convective oven: drying time calculation

The general equation for heat transfer *(Eq.B.1)* is used to compute, once the rest of the parameters are known, the time required for a convective oven to evaporate water and reach the maximum moisture content set for the final product (6 w%). First, mass and energy balances compute the energy required for heating the batch of porridge to reach the boiling point. The heat transfer coefficient of an oven comprises the three mechanisms of heat transfer, namely conduction, convection and radiation. Carson et al. (2006) measured the apparent heat transfer coefficient (h_a) in a domestic convection oven using several techniques. Mass-loss-rate method, which measures the apparent heat transfer coefficient based on the constant rate of mass loss of a dry process (see Table A.6), seems the most accurate for the present case study: ϕ is the mass loss per unit surface area, T_∞ is the temperature in the oven, T_s is the temperature of the surface to be dried and $\lambda_w\ (T_s)$ is the enthalpy of vaporisation of water at the surface temperature.

Table A.6. Domestic convective oven operation

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

Mass-loss-rate method finds a maximum h_a of 28 W m-2 K^{-1} for oven temperatures above 133.5 °C. The working temperature of the domestic oven is set at 180 °C to achieve a surface temperature of 100 °C and thus allowing water to evaporate. Finally, the heat transfer surface is assumed to be two times the surface of the oven tray: heat transfer happens by conduction from the heated tray surface to the porridge, and by convection and radiation from the oven environment to the upper surface of the porridge. No temperature gradient is considered as the porridge is spread on the tray in a thin layer (2 cm) and the cook is periodically stirring the product to ease the drying process. The calculations estimate a value of 5.24 kg of water/h following this method.

A.5. Individual Factors used for cost and capital estimation.

Table A.7. 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)*

Table A.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 ($\boldsymbol{C_D}$)	$C_{Ph} + C_{Eng}$	
	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)*

A.6. Installation Factors for industrial equipment.

Table A.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

A.7. Wholesaling Cost of Raw Materials for Industrial Manufacture.

Table A.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

A.8. Retail Cost of Raw Materials for Artisanal Manufacture.

Table A.11. 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

A.9. Price of energy sources.

Table A.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

A.10. Labour Plant Manufacture Scale.

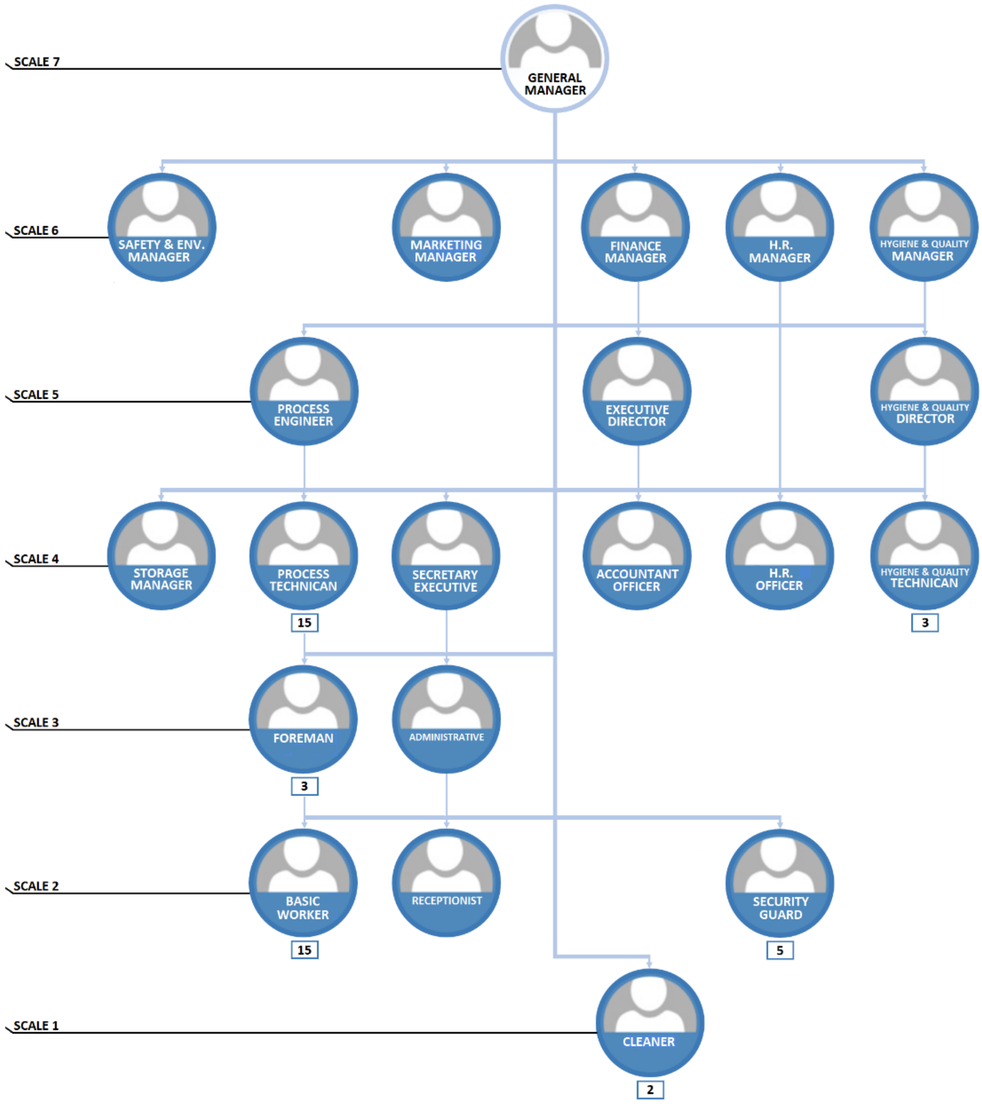


Figure A.1. Company Organisation Chart for Plant Manufacture.

A.11. Labour Plant Distributed Net Scale (High Manufacture Cost).

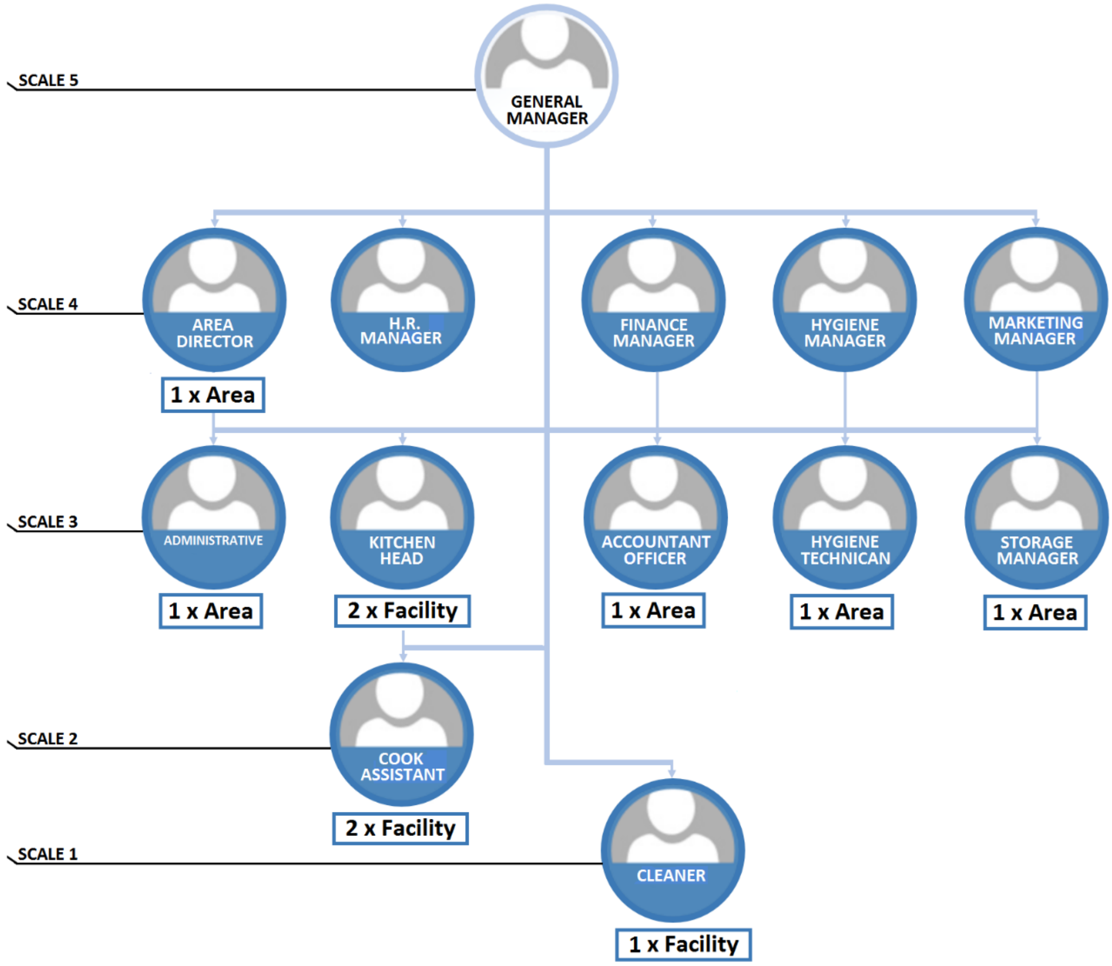


Figure A.2. Company Organisation Chart for Distributed Net with High Manufacture Cost.

A.12. Results for a SP that supply a demand scenario similar to the UK.

Table A.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 A.14. 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*	-

(continues next page)

Table A.14. (cont.)

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*	-

References (of supplementary material)

Alibaba.com. Global trades. Eagle Machine. Full automatic baby food cartoon box packing machine. (2016) (accessed 12/12/2016). http://www.alibaba.com/product-detail/Full-Automatic-Baby-Food-Carton-Box_887898580.html?spm=a2700.7724838.0.0.Qtb4mg, 2016 (accessed: 12/12/2016).

Boundy, B., Diegel, S.W., Wright, L., Davis, S.C., Biomass Energy Data Book, fourth ed., U.S. Department of Energy, 2011, Appendix A, p 201.

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

Dongguan Fuliter Paper Product. Cereal box manufacturer Extract (2016) (accessed: 12/12/2016) https://www.alibaba.com/product-detail/Cereal-box-manufacturer-in-dongguan_1513578342.html.

DSB. Building and renovation cost in UK (2017) (accessed: 11/23/2017) http://www.dsbgeneralbuilding.co.uk/index.php?option=com_content&view=article&id=24&Itemid=86.

Economic Indicators, Chemical Engineering 119 (2012) 84.

Global Dairy Trade. Skim milk powder prices (2016) (accessed: 12/12/2016) https://www.globaldairytrade.info/en/product-results/skim-milk-powder/

Gouda Processing solutions, Drum Dryer (2016) (accessed 7/15/2017) http://www.teknol.eu/wp-content/uploads/2013/12/Drum-dryer.pdf.

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

Government of United Kingdom. Statistical Data set. Gas and electricity prices in the non-domestic sector (2017b) (accessed 02/10/2017) https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector.

Hunan Huacheng Biotech Inc. Natural Dry Malta Extract (2016) (accessed: 12/12/2016) https://www.alibaba.com/product-detail/NSF-cGMP-maunfacture-and-100-natural_60298258200.html.

Indexmundi. Oats Monthly Price (2016a) (accessed: 12/12/2016) http://www.indexmundi.com/commodities/?commodity=oats&months=60.

Indexmundi. Rice Monthly Price (2016b) (accessed: 12/12/2016) http://www.indexmundi.com/commodities/?commodity=rice&months=60.

Indexmundi. Sugar monthly price. (2016c) (accessed: 12/12/2016) http://www.indexmundi.com/commodities/?commodity=sugar&months=60.

Quality Company Formation. Commercial Rent: Price Per Square Foot (2017) (accessed: 11/23/2017) https://www.qualitycompanyformations.co.uk/assets/custom/files/documents/Best_Startup_City_-_Full_Analysis.pdf

Matches. Index of process equipment (2014) (accessed 12/12/2017). http://www.matche.com/equipcost/EquipmentIndex.html.

Shenzhen Huacheng Packaging. Resealable plastic bags for milk powder, coffee, tea or proteins Extract (2016) (accessed: 12/12/2016) https://www.alibaba.com/product-detail/coffee-tea-milk-powder-packing-bags_60190233149.html.

Silla, H., Chemical Process Engineering, Design and Economics, Marcel Dekker Inc., New York, 2003.

Sinnot, R.K., Towler, G., Chemical Engineering Design. Principles, Practice and Economics of Plant and Process Design, second ed., Elsevier, Singapore, 2013.

South West Water. Business Services. 2016-17 Charges Scheme for Business Customers Extract (2016) (accessed: 12/12/2016) http://www.southwestwater.co.uk/media/pdf/6/a/Non-household_Charges_Scheme_2016-2017.pdf.

Suoya Biological Technology. Hydrogenated palm oil in flakes Extract (2016) (accessed: 12/12/2016). https://www.alibaba.com/product-detail/hydrogenated-palm-oil-in-flake_60561866601.html.

Tesco (2017) (accessed: 12/14/2017). http://www.tesco.com.

XYN Can Packaging. Global trades. Food grade powder empty cans Extract (2016) (accessed: 12/12/2016) https://www.alibaba.com/product-detail/Food-grade-powder-empty-cans_60354195244.html.

Appendix B

Energy efficient drum dryer operation

The content of this Appendix has been published in in Energy Procedia, Volume 161 (Almena et al., 2019c)

The modelling and optimisation work were carried out by myself along with the writing of the paper.

Estefania Lopez-Quiroga and Peter Fryer provided guidance and supervision during the research and writing/correction of the paper..

B.1. Abstract

Current environmental policies, which promote a more sustainable food sector, have boosted efforts to reduce energy demand during processing, and particularly during drying operations. One of the routes towards more sustainable and efficient drying processes is the design and implementation of optimal operational routines for the existing drying equipment. In the food industry, drum-dryers are typically employed for the production of food powders from viscous slurries (e.g. starchy slurries). Food powders are used in a wide range of applications in the food industry, from beverage powders (milk or cocoa), instant soups, spices or flours and flavours. In this framework, a model-based optimisation routine is proposed for the operation of a double drum-dryer (product under atmospheric conditions) used in the manufacture of a breakfast cereal porridge. The problem defines optimal steam temperature and optimal rotation speed that minimises the energy demand of the dryer operation for a range of operating conditions that considered different: product formulation, final moisture contents, thickness and initial temperature of the wet slurry. Overall, this work demonstrates the potential of model-based approaches to the design and optimisation of more sustainable and efficient industrial drying technologies in the food sector, which can help in the achievement of short/medium-term energy reduction goals.

B.2. Nomenclature

A_h	heating area (m^2)	h_{i0}	condensation film coefficient ($W/m^2\ {}^oC$)
d_0	external diameter of the drum (m)	k	thermal conductivity ($W/m\ {}^oC$)
di	internal diameter of the drum (m)	L	length of the drum
f_{slurry}	slurry fouling factor ($W/m^2\ {}^oC$)	m	mass (kg)
f_{steam}	steam fouling factor ($W/m^2\ {}^oC$)	$\dot{m}_w$	drying rate (kg/s)
g	gravitational acceleration (m/s^2)	$\dot{Q}$	overall heat transfer rate (kJ/s)
$\dot{Q}_h$	sensible heat rate (kJ/s)	T	temperature (${}^oC$)
r_{d0}	external fouling resistance ($m^2\ {}^oC\ /W$)	U	overall heat transfer coefficient ($W/m^{2o}C$)
r_{di}	internal fouling resistance ($m^2\ {}^oC\ /W$)	x	mass fraction (kg/kg)
t_{res}	residence time (seconds)	$X_{scraper}$	scraper angle (rad)

Greek Symbols		**Subscripts**	
ω	rotating velocity (r.p.m)	*d-s*	drum-slurry
ΔH_{vap}	latent heat of vaporisation (kJ/kg)	*fin*	final
ΔT_{lm}	logarithmic mean temperature difference (${}^oC$)	*gel*	gelatinisation
ρ	density (kg/m^3)	*ini*	initial
μ	viscosity (Pa s)	*l*	liquid
Γ_h	condensate loading (kg/sm)	*m*	drum surface
τ_{slurry}	slurry thickness (m)	*v*	vapour
κ	thermal conduction coefficient ($W/m^{2o}C$)	*w*	water

B.3. Introduction

The Food Industry, the largest manufacture sector in the UK's (FDF, 2018), it is also the largest industrial consumer of energy, with approx. 12% of the total energy use according to the Department of Business and Industrial Strategy (DUKES, 2018). Over the last decade, the sector has undertaken important transformations to meet long-term reduction goals on energy demand: e.g. fuel switching, investment in new energy efficient equipment and low carbon technologies (FDF, 2018). However, food manufacturers still use semi-empirical methods of process design and optimisation that have already exhausted their potential for energy demand reduction. In this context, additional efforts and different approaches to the design of food products and manufacturing processes are required to meet the 2030 sustainability goals (55% energy reduction from the 1990 baseline) (FDF, 2018; United Nations, 2016). One of the actions that could significantly contribute to reduce energy demand during food processing at short and medium term, and the scope of the present work, is the design and implementation of model-based optimal operational routines for existing food manufacturing equipment (Tassou et al., 2014). Recent studies on energy consumption during food manufacture showed that a small number of operations and products are responsible for large proportions of the energy demand and CO2 emissions (Tassou et al., 2014; Griffin et al., 2016). Drying/dehydration operations are commonly used to ensure safety and extend shelf life of foods and powders by processing dried products with moisture contents typically below 10% (Intipunya and Bhandari, 2010). As the water content of foods typically ranges between 75%-90%, the removal of this water content by vaporisation demands a significant amount of energy (2.8 kJ/kg water removed on top of the energy required to change the temperature of the system). On the other hand, starch and starchy products are among the most energy intensive food products (Griffin et al., 2016), as their manufacture involves different stages in which water is added and then removed using thermal processing (Roos et al., 2016). Drum-dryers are usually employed to manufacture food powders from highly viscous pastes, like different types of starchy food products (Kakade et al., 2011; Valous et al., 2002] (e.g. potato flakes, cereal porridges) or fruit powders/flakes (Galaz et al., 2017; Germer et al., 2018), applying high temperatures and short processing times (Courtois, 2013; Islam et al., 2007). A number of works are focused on the characterisation of drum-drying kinetics using thin-layer dehydration models (Henríquez et al., 2014; Qiu et al., 2019) and the effect of process condition on the quality and attributes of the final products (Kakade et al., 2011; Galaz et al., 2017; Germer et al., 2018]. But only a few studies address transport phenomena in detail (Kasiri et al., 2004; Gavrielidou et al., 2002) or proposed formal control/optimisation strategies (Rodriguez et al., 1996; Pua et al., 2010). Thus, modelling and optimising the operation of a double drum-dryer still represents an opportunity for further energy reductions in food processing. In this framework, a model-based approach is presented to design energy-efficient protocols for the operation of a double drum-dryer used in the manufacture of a cereal porridge. The proposed routine assesses a range of operation conditions: (i) product formulation, (ii) final moisture content, (iii) thickness and (iv) initial temperature of the wet slurry to find optimal steam temperature and drum rotation speeds. The overall objective is to minimise the energy consumption of the drum-drying process while ensuring both safety and quality (understood as final moisture content) of the final product. The paper is organised as follows: the drum-drying process is described in Section 3.4, while the model formulation and the optimisation problem are presented in Section 3.5 and Section 3.6, respectively. Results are discussed in Section 3.7, and finally conclusions are outlined in Section 3.8.

B.4. Process description

In double drum-dryers, the product –typically a viscous slurry– is poured onto the external surface of the drums, i.e. metallic hollow cylinders that rotate together near each other in opposite directions and that are continuously filled with superheated steam, as schematically shown in *Fig.B.1*. Inside the cylinders, the steam condensates, raises the temperature (common operating temperatures are above 100°C) and heats up the slurry by conduction throughout the drum walls. After a given residence time, which depends on the drums rotating velocity of ϖ (r.p.m), a set of scrapers (placed at an angle $X_{scraper}$) will remove the dried product from the surface all along the width of each drum (Galaz et al., 2017; Henríquez et al., 2014).

B.5. Drum dryer model

The rate of heat transfer throughout the drums surface controls the drying process Courtois, 2013), so a simple model describing the overall heat transfer rate can be used to simulate the system (Earl, 1983). Considering combined heat transfer modes (i.e. convection and conduction) as depicted in *Fig.B.1*, the overall heat transfer rate $\dot{Q}$ (kJ/s) can be calculated as follows (Earl, 1983; Sinnot and Towler, 2013):

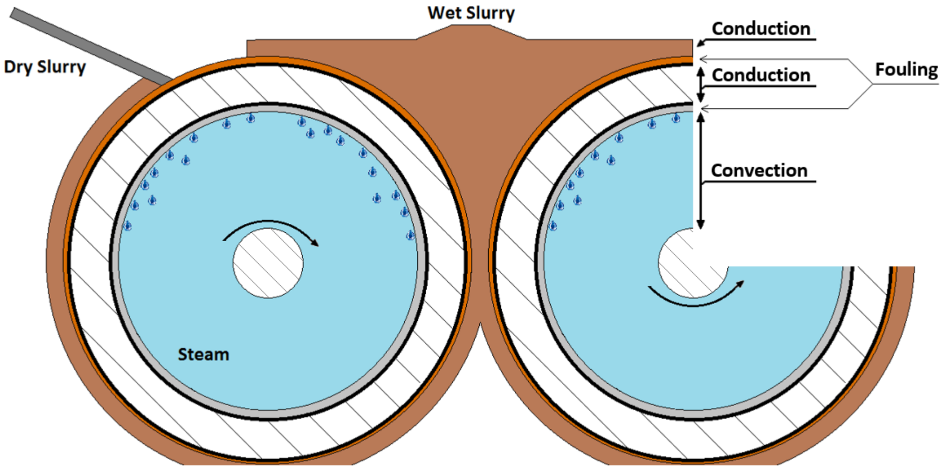


Figure B.1: Double drum-dryer schematics also showing the different heat transfer mechanisms included in the model: convection to define the heat transfer coefficient of the steam inside the drums, and conduction to describe heat transfer (i) through the drum walls and (ii) through the slurry layer. Fouling resistances have been also considered to account for condensed droplets on the inside surface of the drums and for residual slurry on the exterior surface.

$$\dot{Q} = UA_h\Delta T_{lm} \tag{B.1}$$

where A_h (m^2) is the heating surface of the drums, ΔT_{lm}(°C) is the logarithmic mean temperature difference between steam and slurry (considering different inlet and outlet slurry temperatures) and U (W/m^2°C) is the overall heat transfer coefficient, which has been calculated as a total thermal resistance (Sinnot and Towler, 2013) considering all layers and heat transfer mechanisms indicated in *Fig.B.1*:

$$\frac{1}{U} = \frac{1}{h_{i_0}} + \frac{1}{\kappa_{drum}} + \frac{1}{\kappa_{d-s}} + r_{di}\frac{d_0}{d_i} + r_{d0} \tag{B.2}$$

where, d_0(m) is the external diameter of the drum, d_i(m) is the internal diameter of the drum, r_{di}(m^2 °C /W) and r_{d0}(m^2 °C /W) are the resistance for the internal and external fouling, respectively (Sinnot and Towler, 2013):

$$r_{di} = {}^{1}/_{f_{steam}} = {}^{1}/_{3250}\ ;\ r_{d0} = {}^{1}/_{f_{slurry}} = {}^{1}/_{5000} \tag{B.3}$$

The condensation film coefficient for steam inside a horizontal tube h_{i_0} (W/m2 oC) used in B.2 is estimated as (Sinnot and Towler, 2013):

$$h_{i_0} = 0.76\ k_l \left[\frac{\rho_l(\rho_l - \rho_V)g}{\mu_l\ \Gamma_h}\right]^{1/3} \tag{B.4}$$

where k_l(W/m^{o}C), μ_l(Pa s) and ρ_l(kg/m^3) are the thermal conductivity, viscosity and density of the liquid state, ρ_V(kg/m^3) is the density of vapour, Γ_h(kg/ms) is the condensate loading and g(m/s^2) is the gravitational acceleration.

The conduction coefficient for the dryer drum κ_{drum} (W/m^{o}C) also used in B.2 is calculated as follows (Sinnot and Towler, 2013):

$$\kappa_{drum} = \frac{2\ k_m}{d_0\ \ ln\left({}^{d_0}/_{d_i}\right)} \tag{B.5}$$

where k_m(W/m^{o}C) is the thermal conductivity of the drum surface (typically a metallic material). Finally, the conduction coefficient for the slurry κ_{d-s} (W/m ^{o}C) is defined as a function of the thermal conductivity k_{slurry}(W/m^{o}C) and thickness τ_{slurry}(m) of the gelatinised slurry (Sinnot and Towler, 2013):

$$\kappa_{d-s} = \frac{k_{slurry}}{\tau_{slurry}} \tag{B.6}$$

The rate of water evaporation (i.e. drying rate) $\dot{m}_w$ (kg/s) can be calculated from $\dot{Q}$ as follows:

$$\dot{m}_w = {}^{\left(\dot{Q} - \dot{Q}_h\right)}\Big/_{\Delta H_{vap}} \tag{B.7}$$

where ΔH_{vap}(kJ/kg) is the vaporisation latent heat for water and $\dot{Q}_h$ is the sensible heat rate needed to heat up the slurry up to its vaporisation temperature. From the drying rate, the final water content in the dried product can be obtained through a simple mass balance:

$$x_w^{fin} = \left[\frac{m_{slurry}^{ini} x_w^{ini} - t_{res}\dot{m}_w}{\rho_{slurry}\, A_h\, \tau_{slurry} - t_{res}\dot{m}_w}\right] \tag{B.8}$$

where m_{slurry}^{ini} is the initial slurry mass, x_w^{ini} is the initial water content in the slurry (as mass fraction), ρ_{slurry} is the density of the slurry (kg/m^3) and $t_{res} = 60/\omega X_{scraper}$ is the residence time in seconds.

B.6. Energy efficient operation conditions

A number of variables must be considered when designing an efficient operation for a double-drum dryer. First of all, the initial water content in the slurry; this, together with the target final water content x_w^{target}, defines the amount of water that needs to be removed. The thickness of the slurry sheet deposited on the drums also affects the rate of water removal (thicker sheets imply higher product throughputs) and can be varied by adjusting the gap (clearance) between drums. The overall heat transfer rate depends directly on the drums dimensions (length L and diameter d_0), and angle of the scrapers, as they defined the available heating surface. Finally, from an operational point of view, there are two main variables that can be manipulated (Courtois, 2013) (and so controlled and/or optimised):

(i) the input steam temperature T_{steam} (^{o}C), which depends on the slurry formulation (e.g. water content, flour mixture) and it is chosen according to the desired characteristics of the final dried product (Courtois, 2013).

(ii) the rotation speed of the drums ω (r.p.m), which is set to adjust the final moisture content of the product and defines the residence time of the operation.

According to this, different slurry formulations and thicknesses (i.e. product conditions) can be assessed to find those operational conditions - defined through ω *and* T_{steam} - that lead to reduced energy demand scenarios (Q_{red}). Formally, this can be done by minimising Q subject to the process dynamics defined by equations B.1-B.8 and the following constraints:

$$x_w^{fin} = x_w^{target} \tag{B.9}$$

$$\dot{m}_w = \dot{m}_w^{target} \tag{B.10}$$

$$\dot{Q} = \dot{Q}_{target} \tag{B.11}$$

$$100 \leq T_{steam}(°\mathrm{C}) \leq 300 \tag{B.12}$$

$$1.5 \leq \omega(\mathrm{r.p.m.}) \leq 15 \tag{B.13}$$

where equation B.9 is an end point constraint related to the target final moisture content and equations B.10 and B.11 are related to the fulfilment of mass and energy balances. The upper and lower bounds for the manipulated variables are defined by B.12 and B.13 according to equipment technical specifications.

B.7. Results and Discussion.

To solve the optimisation problem proposed in Section 3.6, the dimensions of the drums have been set to L = 2 m and d_0 = 1 m, with $X_{scraper}$ = 5/6, which leads to a heating surface for each drum of $A_h = 5\pi L d_0/3$. It has been also considered that the slurry is cooked in a previous step, and the corresponding gelatinisation temperature of the mixture is used as the slurry temperature T_{slurry} (°C) when is poured onto the drums. Results show wo different slurry compositions obtained using (i) only oat flour and (ii) a mixture of rice, maize and oat flours at varying mass fractions, with a constant throughput in both cases of $\dot{m}_{slurry}$= 250 kg/h. The effect of different initial and final moisture contents, as well as the effect of the slurry thickness have been evaluated.

B.7.1. Oat slurry

The effect of the final moisture content in the dried product has been evaluated for a (gelatinised) slurry with an initial water content of $x_w^{ini} = 0.8$ (kg water/kg slurry). The cereal used in this case was oat flour ($x_{oat}^{ini} = 0.2$). Thermal properties for oat flour – also for rice and maize flours –have been taken from (Onita and Ivan, 2005). Table B.1 presents optimal steam temperatures T_{steam} and drum velocities ω, alongside energy consumption values for the double-drum dryer $\dot{Q}$(kJ/s). These results show that the energy consumption of the double-drum dryer increases (with linear dependence) when the final moisture content decreases, reaching its maximum (652 kJ/s) for the lowest moisture target (4%) assessed. The increase on the energy demand is also linked to higher steam temperatures and shorter residence times (i.e. faster rotation of the drums).

Table B.1. Optimal values for the manipulated variables together with corresponding energy consumption values calculated considering an oat slurry (80% water, 20% oat flour) and a range of final moisture contents.

Target final moisture content (%)	T_{steam} (ºC)	ω (rpm)	$\dot{Q}_{red}$(kJ/s)
4%	169	5.3	652
6%	167	5.2	635
8%	164	5.1	618
10%	162	5.0	601
12%	159	4.8	584

The variation of the manipulated variables for different thicknesses of the oat slurry is shown in *Fig.B.2(a)*. Results suggest that thinner slurries can be dried in shorter times (i.e.

faster *ω*) and at lower steam temperatures. As the slurry thickness increases, a larger amount of water must be evaporated. This results in a gradual rise of the steam temperature (i.e. faster heat transfer rates) coupled with a (steeper) reduction of the residence times (i.e. faster *ω*), which allows more time to reach the final target moisture content –fixed at 8% for this particular case.

Fig.B.2(b) presents T_{steam} and ω values corresponding to varying initial moisture contents of the oat slurry. In this case both manipulated variables show similar trends, with values rising as the initial water content of the slurry increases from 60% to 90%, and residence times decrease for higher T_{steam}, similarly to data presented in Table B.1.

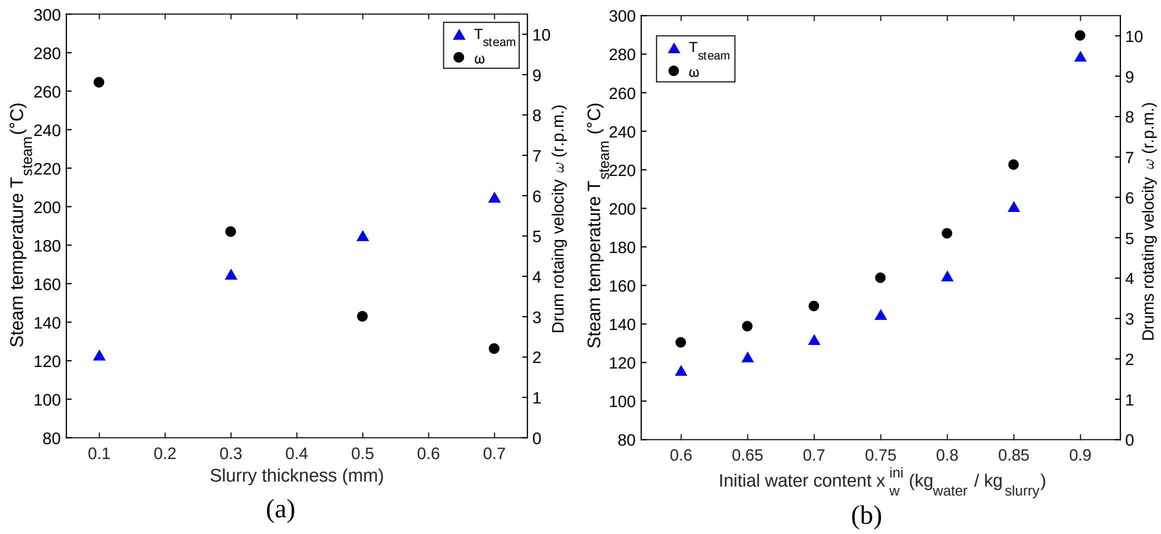


Figure B.2: Evolution of the manipulated variables T_{steam} (ºC) and ω (r.p.m) for an oat slurry with: (a) 80% initial water content and increasing thickness; (b) constant thickness and initial water content ranging from 60% to 80%.

B.7.2. Cereal mix slurry

The effect of different product formulation on the energy consumption of the double-drum dryer has been investigated using a varying mixture of oat, rice and maize flour that represents 20% of the slurry initial mass. The thickness of the sheet has been kept constant, as well as the initial water content (set up to 80%), which caused no variations on the drying rates, i.e. residence times and drums rotating velocities. Therefore, results for the steam temperature T_{steam} and the overall energy consumption of the double-drum $\dot{Q}$ are shown in *Fig.B.3(a)* and 3(b), respectively, using ternary graphs to represent all the possible flour combinations - each component (oat, rice or maize) varying from 0% to 100%.

Slightly higher steam temperatures (around 168^{o}C-170^{o}C) are required to dry mixtures of rice and oat flours (target final moisture set up to 8%), while mixtures with higher contents of maize flour could be processed at temperatures around 163^{o}C. However, this trend does not translate in terms of energy consumption: mixtures of rice and oat flours resulted in lower $\dot{Q}$ values (580 kJ/s – 590 kJ/s), intermediate energy values (~600 kJ/s) corresponded to maize and oat mixtures, while flour with oats as single components led to the highest energy consumption in the system (~615 kJ/s). This is a consequence of the different gelatinisation temperatures of the slurries. As $T_{gel}^{oat} < T_{gel}^{maiz} < T_{gel}^{rice}$, ΔT_{lm} (i.e. the difference between T_{slurry} and T_{steam}) is smaller for rice than for oats, which according to equation B.1 must lead to also smaller values of $\dot{Q}$ for rice than for oats, as suggested by results presented in *Fig.B.3(b)*.

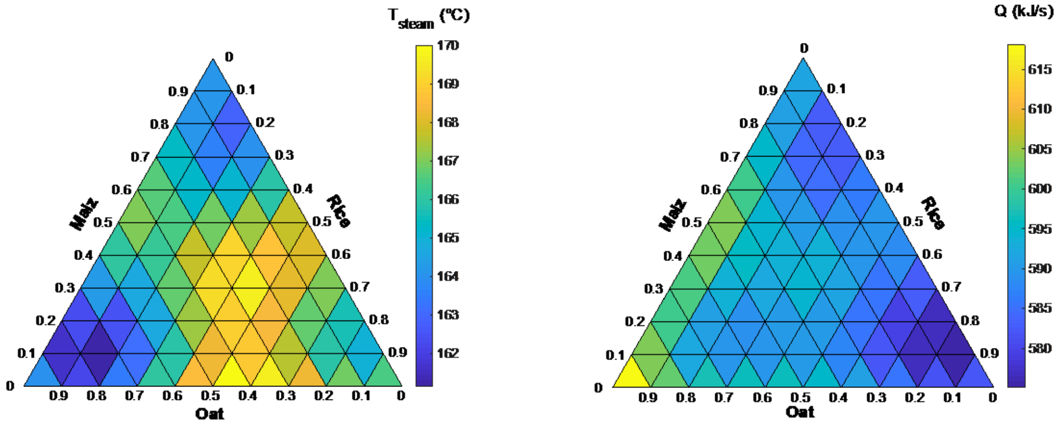


Figure B.3: (a) Steam temperatures and (b) energy consumption values obtained for slurries with a ternary composition of flours (rice, oat and maize). The initial water content is 80%, with a constant slurry thickness of 0.3 mm and a target final moisture content of 8%.

B.8. Conclusions

A model-based approach to the design of energy-efficient drying processes - one of the most energy intensive operations used in food manufacture - has been presented. Focusing on the manufacture of a cereal porridge, optimal steam temperatures and drum rotating velocities have been obtained for a double-drum dryer that minimise the overall energy required to dry the slurry. Different process variables, such as product formulation (e.g. flour composition, initial and final water content) or slurry throughputs (i.e. sheet thicknesses) have been assessed. Results reveal that there is potential for energy demand reduction by adjusting the water content (both initial and final) in the product formulation including the slurry throughput (i.e. slurry thickness) as variable to be optimised: thicker slurries require drying processes defined by higher steam temperatures and longer residence times, while medium/low temperatures and shorter residence times will be preferable for thinner sheets – a trade-off could be found through multi-objective optimisation (minimise energy, maximise drying rate).

This work demonstrates that further energy reductions can be achieved at short and medium term by using model-based approaches to the design and optimisation of current processing technologies. In addition, by setting the basis for more sustainable processing of food powders – products that are easy to use, pack, distribute and handle – this works also contributes to the development of an alternative supply scenario for dried products based on distributive manufacturing principles, where powders and dried components could be shipped (at lower costs), and rehydrated and/or used for other manufacture processes in points located closer to the consumer.

B.9. Bibliography

Courtois, F., Roller and drum drying for food powder production, Handbook of Food Powders: Processes and Properties (2013) 85-104. https://doi.org/10.1533/9780857098672.1.85

DUKES. Digest of UK Energy Statistics. Department of Business and Industrial Strategy, 2018. https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes#2018

Earl, R.L. Unit operations in food processing (2nd ed.), Pergamon, Oxford, 1983. ISBN: 978-0-08-025536-1. https://doi.org/10.1016/C2009-0-00556-X

FDF. Food and drink federation, 2018. Stats at a glance. www.fdf.org.uk

Galaz, P., Valdenegro, M., Ramírez, C., Nuñez, H., Almonacid, S., Simpson, R., Effect of drum drying temperature on drying kinetic and polyphenol contents in pomegranate peel, Journal of Food Engineering 208 (2017) 19-27. https://doi.org/10.1016/j.jfoodeng.2017.04.002

Gavrielidou, M.A., Valous, N.A., Karapantsios, T.D., Raphaelides, S.N., Heat transport to a starch slurry gelatinizing between the drums of a double drum dryer, Journal of Food Engineering 54 (1) (2002) 45-58. https://doi.org/10.1016/S0260-8774(01)00184-4

Germer, S.P.M., Tonin, I.P., de Aguirre, J.M., Alvim, I.D., Ferrari, C.C., Influence of process variables on the drum drying of mango pulp, Drying Technology 36 (12) (2018) 1488-1500. https://doi.org/10.1080/07373937.2017.1410707

Griffin, P.W., Hammond, G.P., Norman, J.B., Industrial energy use and carbon emissions reduction: a UK perspective, Wiley Interdisciplinary Reviews: Energy and Environment 5 (6) (2016) 684-714. https://doi.org/10.1002/wene.212

Henríquez, C., Córdova, A., Almonacid, S., Saavedra, J., Kinetic modeling of phenolic compound degradation during drum-drying of apple peel by-products, Journal of Food Engineering 143 (2014) 146-153. https://doi.org/10.1016/j.jfoodeng.2014.06.037

Intipunya, P., Bhandari, B.R., In Chemical deterioration and physical instability of food powders, Chapter 22 (2010) 663-700, Woodhead Publishing Series in Food Science, Technology and Nutrition, Chemical Deterioration and Physical Instability of Food and Beverages. ISBN 978-1-845-69495-1. https://doi.org/10.1533/9781845699260.3.663

Islam, Md.R., Thaker, K.S., Mujumdar, A.S., A diffusion model for a drum dryer subjected to conduction, convection, and radiant heat input, Drying Technology 25 (6) (2007) 1033-1043. https://doi.org/10.1080/07373930701397467

Kakade, R.H., Das, H., Ali, S, Performance evaluation of a double drum dryer for potato flake production, Journal of Food Science and Technology 48 (4) (2011) 432-439. https://doi.org/10.1007/s13197-010-0184-0

Kasiri, N., Hasanzadeh, M.A., Moghadam, M., Mathematical modeling and computer simulation of a drum dryer, Iranian Journal of Science and Technology, Transaction B: Engineering 28 (6 B (2004) 679-687.

Onita, N., Ivan, E., Estimation of the specific heat and thermal conductivity of foods only by their classes of substances contents (water proteins, fats, carbohydrates, fibers and ash), Agroalimentary Processes and Technologies 2 (1) (2005) 217-222.

Pua, C.K., Hamid, N.S.Abd., Tan, C.P., Mirhosseini, H., Rahman, R.B.Abd., Rusul, G., Optimization of drum drying processing parameters for production of jackfruit (Artocarpus heterophyllus) powder using response surface methodology, LWT - Food Science and Technology 43 (2) (2010) 343-349. https://doi.org/10.1016/j.lwt.2009.08.011

Qiu, J., Kloosterboer, K., Guo, Y., Boom, R.M., Schutyser, M.A.I., Conductive thin film drying kinetics relevant to drum drying, Journal of Food Engineering 242 (2019) 68-75. https://doi.org/10.1016/j.jfoodeng.2018.08.021

Rodriguez, G., Vasseur, J., Courtois, F., Design and control of drum dryers for the food industry. Part 2. Automatic control, Journal of Food Engineering 30 (1-2) (1996) 171-183. https://doi.org/10.1016/0260-8774(95)00054-2

Roos Y.H., Fryer P.J., Knorr D., Schuchmann P., Schröen K., Schutyser M.A.I., Trystram G., Windhab E.J. Food engineering at multiple scales: case studies, challenges and the future – a European perspective, Food Engineering Reviews 8 (2016) 91–115. https://doi.org/10.1007/s12393-015-9125-z

Sinnot, R.K. & Towler, G. Chemical Engineering Design. Principles, Practice and Economics of Plant and Process Design, 2nd Edition. Elsevier Singapore. 2013; ISBN 978-0-08-096659-5.

Tassou, S.A., Kolokotroni, M., Gowreesunker, B., Stojceska, V., Azapagic, A., Fryer, P., Bakalis, S., Energy demand and reduction opportunities in the UK food chain, Proceedings of Institution of Civil Engineers: Energy 167 (3) (2014) 162-170. https://doi.org/10.1680/ener.14.00014

United Nations. Transforming our world: the 2030 Agenda for Sustainable Development, 2016. A/RES/70/1;

Valous, N.A., Gavrielidou, M.A., Karapantsios, T.D., Kostoglou, M., Performance of a double drum dryer for producing pregelatinized maize starches, Journal of Food Engineering 51 (3) (2002) 171-183. https://doi.org/10.1016/S0260-8774(01)00041-3

Appendix C

Supplementary material for Chapter 4

Table C.1. Equipment selected for HM and FI methods

Equipment	Model	Volume (l)	Power (kW)	Price ($)
Stand Mixer	Kenwood Chef Elite	4.6	1.2	260
Convection oven	Bosch HBA73R150B	70	3.5 (max)	500
Kitchen scale	Smart Weigh PL11B	-	-	20
Bread Slicer	Bamboo Bread Slicer	-	-	20
Fridge-Freezer	Kenwood- ksbsdx15	Fridge: 368	433 (kWh/year)	600

Table C.2. Equipment selected for DM method

Equipment	Model	Capacity	Power (kW)	Price ($)
Spiral Mixer	Sammic SME-50	40 kg	2.2	2,730
Hydraulic divider	Yoslon YSN-Y20	20 pieces	1.5	3,500
Bread Moulder	Juyoumech-200	1,500 pieces/h	2.4	4,000
Proving Cabinet	Sagi KAF1N	42 loaves	2.9	4,500
Rack oven	KH KL-32	52 loaves	20.0 (max)	6,000
Bread Slicer	Hongling HLM-25	2 loaf/min	0.3	380

Table C.3. Equipment selected for industrial method

Equipment	Model	Capacity	Power (kW)	Price ($)
Ribbon blender	Paul O. Abbe	-	Scalable Size	-
Volumetric pressure divider	SLIM 1400	1,750 pieces/h	1.5	14,000
Conical rounder	Haidier HDR-R2	2,400 pieces/h	0.8	5,000
Bread machine	KH-MBX-320	5,000 pieces/h	1.5	12,700
Spiral proving machine	Hitrees SP-1	200 – 5,000 pieces/h	32.0	20,000
Seed sprinkler	Newest NT-B1500	10,000 kg/h	0.5	20,000
Tunnel oven	Konig MDI Stratos	Customised length	48.0	2,750 $/m
Spiral cooling tower	Omega-bake cooling tower	200 – 5,000 pieces/h	Regression from data	70,000
Bread slicer	NEWEEK FT-01	25 loaf/min	3.0	8,000
Packing machine	Coretamp KT-250	10,000 loaf/h	5.5	30,000

Table C.4. Parameters used for the mass and energy balance

Parameter [units]	Symbol	Value (*Source*)
Heat capacity bread [kJ/kg K]	cp_{bread}	2.389 *(Le-bail et al., 2010)*
Heat capacity crust [kJ/kg K]	cp_{crust}	2.089 *(Le-bail et al., 2010)*
Heat capacity crumb [kJ/kg K]	cp_{crumb}	2.615 *(Le-bail et al., 2010)*
Heat capacity dough [kJ/kg K]	$cp_{raw-dough}$	$2.984 - 0.834\mathrm{x}_{\mathrm{water}} + 0.007\mathrm{T}$ *(Matuda et al., 2011)*
Heat capacity stainless steel [kJ/kg K]	cp_{SS}	0.51
Heat capacity aluminium [kJ/kg K]	cp_{Al}	0.90
Enthalpy vaporisation of water [kJ/kg K]	λ_{water}	2,257
Density of water [kg/m^3]	ρ_{water}	998.2
Density of gas free dough [kg/m^3]	ρ_{dough}	1,270 (*Campbell et al., 1993)*
Bulk density of wheat flour [kg/m^3]	ρ_{flour}	593;
Bulk density of salt [kg/m^3]	ρ_{salt}	1,282;
Bulk density of yeast [kg/m^3]	ρ_{yeast}	945;
Bulk density bread improver [kg/m^3]	$\rho_{improver}$	513;
Bulk density of sugar [kg/m^3]	ρ_{sugar}	705;
Density of margarine [kg/m^3]	$\rho_{margarine}$	959.47;
Low heating value of natural gas [kJ/m^3]	$LHV_{nat\ gas}$	36,624.9;
Low heating value of fuel oil [kJ/kg]	LHV_{fuel}	38,700.0;

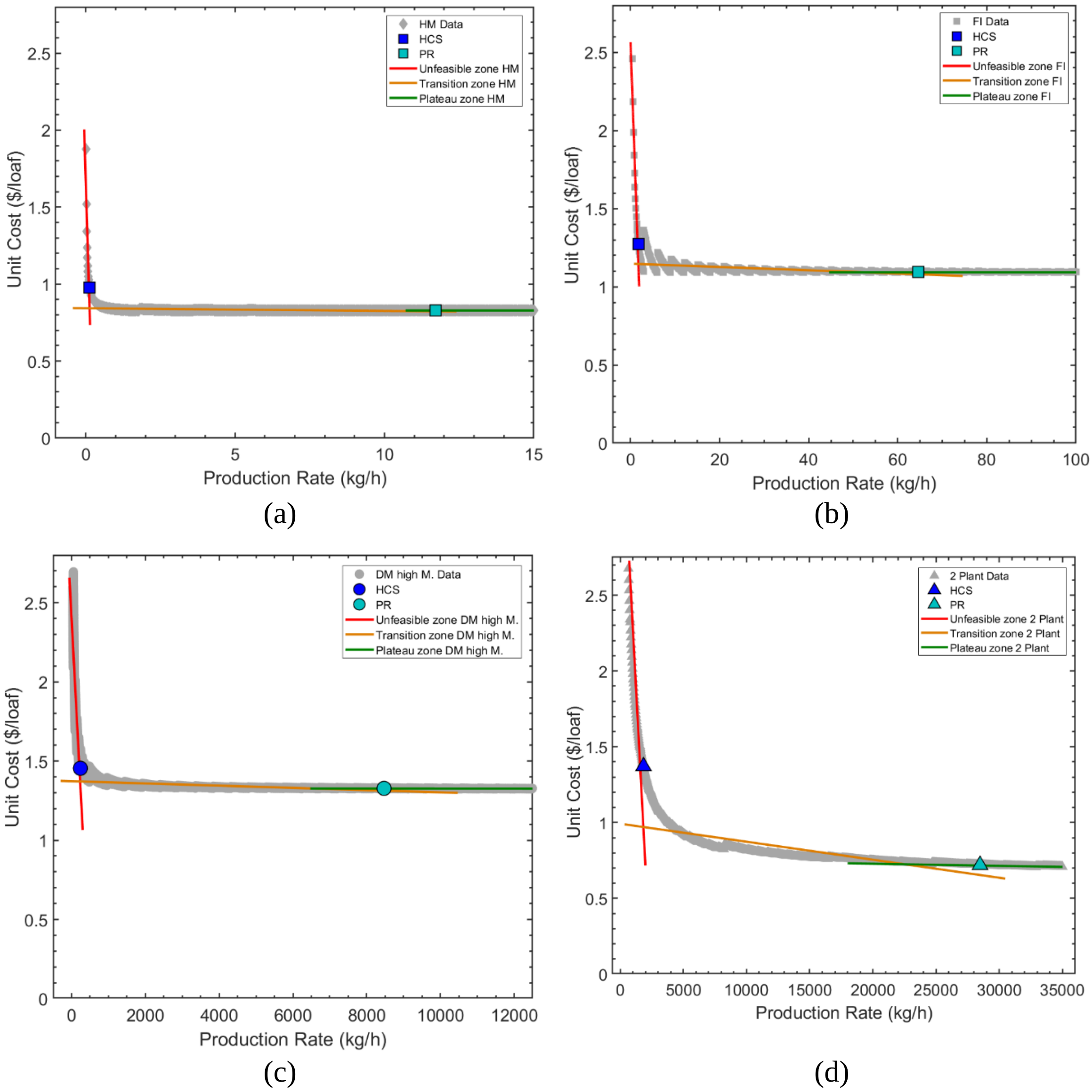


Figure C1. Identification of the three different operation regions defined in this work for artisan manufacturing scenarios.

Appendix D

Supplementary material for Chapter 5

Nomenclature

Lowercase

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

Uppercase

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

Subscripts

0	starting point	*lb*	lower bound
app	apparent	*lm*	logarithmic mean
b	freezing barrel	*mix*	pre-frozen mix
b-d	batches in a daily base	*msnf*	milk solids non fat
bf	baffle	*o*	outer
c	cylinder	*out*	outlet
cond	condensate/condenser	*p*	plate
cont	continuous phase	*p-d*	actual productive time in a daily base
e	external	*past*	pasteurisation
evap	evaporator	*PHE*	plate heat exchanger
f	fusion	*pt*	port
fd	freezing point depression	*raw*	pre-pasteurised mix
hom	homogenised	*ref*	refrigerant

i	inner	reg	regeneration
ic	ice cream	ss	stainless steel
ice	ice phase	st	solute
ii, jj	iteration step	sv	solvent
IF	initial freezing	t	turbine
im	impeller	u	useful
in	inlet	ub	upper bound
j	individual food component	v	vessel
jk	jacket	w	water
k	dissolved substance	$wall$	property by the wall
Greek Symbols			
$\dot{\gamma}$	shear rate (s^{-1})	λ	thermal conductivity (W m^{-1} k^{-1})
Γ_h	horizontal tube loading (kg m^{-1} s^{-1})	μ	viscosity (Pa s)
δ	thickness (m)	ρ	density (kg m^{-3})
ε	volume fraction	χ	conservation property
η	yield	ω	rotational speed (s^{-1})

D.1. Freezing point depression calculation (Leighton, 1927; Tharp and Young, 2013)

First the molecular weight formula is defined:

$$T_{fd} = k_{sv} \frac{x'_{st}}{M_{st}} \qquad \text{D.1}$$

where T_{fd} is the freezing point depression ($°C$), k_{sv} is the solvent factor (1.86 for water), M_{st} is the molecular weight of the dissolved substance and x'_{st} is the dissolved substance grams per 100 grams of water.

The equivalent of sucrose (SE) is used for computing the contribution of any component that represent a source of soluble solids to the freezing point depression. It is calculated from the freezing point factor (FPF), the inverse molecular weight ratio of the dissolved substance and the sucrose. The effect of milk salts needs to be computed separately.

$$SE_k = x_k \times FPF \times 100 = x_k \frac{M_{sucrose}}{M_k} \times 100 \quad \text{D.2}$$

$$x'_{st} = \frac{\sum SE_k \times 100}{x_w \times 100} \quad \text{D.3}$$

In which k index represent the dissolved substance, x_k is the weight fraction of component k, $M_{sucrose}$ is the molecular weight of sucrose (342.3 g/mol) and M_k is the molecular weight of k. Within the formulations contained here, the sources of soluble solids are sugar, molasses, soya lecithin, chocolate powder, vanilla extract, banana puree, glucose syrup, glucose-fructose syrup (k therefore runs from 1 to 8). The glucose syrup (428 g/mol) and glucose-fructose syrup (298 g/mol) average molecular weight are obtained from Goff and Hartel (2013). The rest contribute with the sugar content (USDA, 2020) that is assumed to be sucrose so their FPF is 1.

Once x' is computed, T_{fd} can be obtained from Eq.D.4, a correlation found when minimizing the sum of squared error (R^2 factor of 0.999) from *Table 6.1* in Goff and Hartel (2013).

$$T_{fd} = 9.4915 \times 10^{-5}\, x'^2 + 6.1231 \times 10^{-2} x' \quad \text{D.4}$$

The contribution of milk-solid-non-fat (D_S) is computed as follows:

$$T_{fd}{}^{msnf} = \frac{x_{msnf} \times 2.37}{x_w} \quad \text{D.5}$$

Finally, the total freezing point depression –i.e. initial freezing point– of the ice cream mix (T_{IF}) is:

$$T_{IF} = T_{fd} + T_{fd}{}^{msnf} \quad \text{D.6}$$

D.2. Thermal properties of food components.

Table D.1. Thermal properties models for food components ($-40\ °C \leq T \leq 150\ °C$):

Thermal Property	Food Component	Thermal Property Model
Specific Heat $\left[{}^{J}/_{kg\ K}\right]$	Fat	$cp_{fat} = (1984.2 + 1.4733\ \mathrm{T} - 0.0048008\ \mathrm{T}^2)$
	Protein	$cp_{prot} = (2008.2 + 1.2089\ \mathrm{T} - 0.0013129\ \mathrm{T}^2)$
	Carbohydrate	$cp_{carbh} = (1548.8 + 1.9625\ \mathrm{T} - 0.0059399\ \mathrm{T}^2)$
	Fibre	$cp_{fib} = (1845.9 + 1.8306\ \mathrm{T} - 0.0046509\ \mathrm{T}^2)$
	Ash	$cp_{ash} = (1092.6 + 1.8896\ \mathrm{T} - 0.0036817\ \mathrm{T}^2)$
	Water	
	$T > T_{IF}$	$cp_{w1} = (4176.2 - 0.090864\ \mathrm{T} + 0.0054731\ \mathrm{T}^2)$
	$T < T_{IF}$	$cp_{w1} = (4081.7 - 5.3062\ \mathrm{T} + 0.99516\ \mathrm{T}^2)$
	Ice	$cp_{ice} = (2062.3 + 6.0769\ \mathrm{T})$
	Air	$\frac{cp_{air}}{R} = (2000 + 3.355\ \mathrm{T} + 0.575\ 10^{-3}\ \mathrm{T}^2 - 0.016\ 10^{-5}\ \mathrm{T}^3)$
Density $\left[{}^{kg}/_{m^3}\right]$	Fat	$\rho_{fat} = 925.59 - 0.41757\ \mathrm{T}$
	Protein	$\rho_{prot} = 1329.9 - 0.5184\ \mathrm{T}$
	Carbohydrate	$\rho_{carbh} = 1599.1 - 0.31046\ \mathrm{T}$
	Fibre	$\rho_{fib} = 1311.5 - 0.36589\ \mathrm{T}$
	Ash	$\rho_{ash} = 2423.8 - 0.28063\ \mathrm{T}$
	Water	$\rho_{w} = 997.18 + 0.0031439\ \mathrm{T} - 0.0037574\ \mathrm{T}^2$
	Ice	$\rho_{ice} = 916.89 - 0.13071\ \mathrm{T}$
	Air (ideal gas)	$\rho_{air} = \left(\frac{28.966}{1000} + \frac{\mathrm{P}}{8.314\ (\mathrm{T} + 273)}\right)$
Thermal Conductivity $\left[{}^{W}/_{m\ K}\right]$	Fat	$\lambda_{fat} = (0.18071 - 0.0027604\ \mathrm{T} - 0.00000017749\ \mathrm{T}^2)$
	Protein	$\lambda_{prot} = (0.17881 + 0.0011958\ \mathrm{T} - 0.0000027178\ \mathrm{T}^2)$
	Carbohydrate	$\lambda_{carbh} = (0.20141 + 0.0013874\ \mathrm{T} - 0.0000043312\ \mathrm{T}^2)$
	Fibre	$\lambda_{fib} = (0.18331 + 0.0012497\ \mathrm{T} - 0.0000031683\ \mathrm{T}^2)$
	Ash	$\lambda_{ash} = (0.32962 + 0.0014011\ \mathrm{T} - 0.0000029069\ \mathrm{T}^2)$
	Water	$\lambda_{w} = (0.57109 + 0.0017625\ \mathrm{T} - 0.0000067306\ \mathrm{T}^2)$
	Ice	$\lambda_{ice} = (2.2196 - 0.0062489\ \mathrm{T} + 0.00010154\ \mathrm{T}^2)$
	Air	$\lambda_{air} = 0.025$

D.4. Batch pasteuriser design

D.4.1. Vessel design

$$m_{batch} = \frac{\dot{m}_{mix}}{N_{b-d}} \times t_{p-d} \qquad \text{D.13}$$

$$V_{batch} = \frac{m_{batch}}{\rho_{mix}{}^{raw}(T_{blending})} \qquad \text{D.14}$$

The blending and pasteurisation are carried out under atmospheric pressure conditions. Then, the rules of thumb (Walas, 1990) recommend a torispherical head for the vessel. The ratio length/diameter for the vessel is assumed to be 2, being the level of the liquid the same value as the diameter of the vessel (Walas, 1990). On this basis the normalised –increment of 15cm– diameter of the designed vessel (D_v) is:

$$D_v = \left[\left(\frac{V_{batch}}{\frac{\pi}{4} + 0.0809} \right)^{1/3} \times \left(\frac{1}{0.15} \right) \right] \times 0.15 \qquad \text{D.15}$$

The volume of the vessel with torispherical head would therefore be:

$$V_v = \frac{\pi}{4} D_v{}^2 L_v + 2 \times 0.0809 D_v{}^3 \qquad \text{D.16}$$

The rest of the design dimensions are dependent on the vessel diameter, following the rules of thumb. For improving the blending of the mix, a baffled vessel with four baffles is considered:

$$L_t = \tfrac{1}{3} D_v \;\; ; \;\; H_t = \tfrac{1}{3} D_v \;\; ; \;\; \delta_t = \tfrac{1}{15} D_v \;\; ; \;\; \delta_b = \tfrac{1}{10} D_v \qquad \text{D.17}$$

where L_t is the length of the turbine, H_t is the distance from the turbine and the bottom of the vessel, δ_t is the thickness of the turbine blade and δ_{bf} is the width of the baffle.

D.4.2. Design of the heat transfer jacket

The external heating by a jacket will be the first option for heating the mix. The energy balance will compute the energy flow that is required to heat the batch of mix up to the pasteurisation temperature. There is only sensible heat involved:

$$\dot{Q}_{heat} = \frac{M_{batch}}{t_{heating}} \int_{T_{blending}}^{T_{past}} c_{p_{mix}} dT \tag{D.18}$$

The heat flow will depend on the time is used for heating the mix. Lower heating times imply higher heat flow, so it requires higher heat transfer coefficient. The general equation for heat transfer across a surface will provide the theoretical overall heat transfer coefficient for this operation ($U_{theoretical}$):

$$\dot{Q}_{heat} = U_{theoretical} \cdot A_{heat-trans} \cdot T_{lm} \tag{D.19}$$

where the heat transfer surface is the internal surface of the vessel, approached to a cylinder surface with just the bottom base, considering the already designed vessel and the level of the mix already set (D_v):

$$A_{heat-trans} = D_v 2\pi \frac{D_v}{2} + \pi \left(\frac{D_v}{2}\right)^2 \tag{D.20}$$

The value of $U_{theoretical}$ can be thus calculated. The design of the jacket should guarantee the same value (${U_{Design}}^{v-j}$) for heating the mix to the requested temperature. Assuming that the value of the overall heat transfer coefficient through a wall is the sum of the different heat transfer resistances involving the current process:

$$\frac{1}{U_{Design}{}^{v-j}} = \frac{1}{h_i} + \frac{1}{f_{ic}} + \frac{A_i \, ln\left(\frac{D_v + \delta_v}{D_v}\right)}{2\pi D_v \lambda_v} + \frac{1}{f_w} + \frac{A_i}{A_o h_0} \qquad \text{D.21}$$

being h_i the heat transfer coefficient on the mix side, λ_v is the thermal conductivity of the vessel material, $f_{ice\ cream}$ and f_{water} the fouling factors of ice cream and water respectively (Sinnot and Towler, 2013), δ_v is the vessel thickness averaged as 8mm (Green and Perry, 2008), A_i and A_o are the internal and external wet surfaces, and h_0 is the heat transfer coefficient on the jacket side.

The fouling factor are already set, and the conductivity resistance, only depending on the vessel design, can be already calculated and will remain constant. The overall heat transfer coefficient has been defined to the internal vessel surface ($A_i \equiv A_{heat-trans}$), so the coefficient on the jacket size (h_o) has to be corrected considering the external vessel surface (A_o) that accounts the thickness of the material (δ_v). The heat transfer coefficients on the mix and the jacket side will though depend on the design and need to be computed as follows:

D.4.2.1. Heat transfer coefficient on the mix side (h_i)

The value of this coefficient depends on the heat transfer equipment and the type of turbine used for the agitation. Based on Chilton, Drew and Jebens correlations for heat transfer in agitated vessels, Sinnot and Towler (2012) advise the following correlation for a baffled vessel with a flat-blade turbine in a stirring regime of Reynold values from 2,000 to 700,000:

$$Nu = 1.10\, Re^{0.63} Pr^{0.33} \left(\frac{\mu_{mix}}{\mu_{wall}}\right)^{0.14} \qquad \text{D.22}$$

The rotational speed of the blades (N_t) should be high enough for achieving a Re higher than 2,000. The initial speed set is 3.81 m/min according to thumb rules (Walas, 1990), that must be transformed to s^{-1}:

$$N_{t_0} = \frac{3.81}{L_t/_2}\left(\frac{1}{60}\right) \quad \text{D.23}$$

The speed of the tips applies shear stress to the ice cream mix. As non-Newtonian fluid, the viscosity of the mix will vary with the rational speed. The following correlation is found to calculate the shear rate of the impeller on a non-Newtonian fluid (Calderbank and Moo-Young; Campesi et al 2009):

$$\dot{\gamma}_{app} = k_{impeller} \left(\frac{4n_{mix}}{3n_{mix}+1}\right)^{\frac{n_{mix}}{n_{mix}-1}} \omega_t \quad \text{D.24}$$

where $k_{impeller}$ is a constant dependant on the type of impeller and n_{mix} is the flow index of the mix. Rushton turbines are assumed to be used for the agitation of the mix, and $k_{impeller}$ takes a value of 11.4. The shear rate in the region close to the wall will necessary be lower due to the friction to the walls and the baffles. Mitsuishi and Miyari (1973) based on experimental data found that the shear rate on the wall is approximately half of the shear rate of the agitated fluid in the impeller $\dot{\gamma}_{wall} = \frac{1}{2}\dot{\gamma}_{app}$. The non-Newtonian behaviour allows to calculate the viscosity of the mix as a power law fluid, taking n_{mix} as 0.55 (Arellano et al., 2013) and the consistency of the mix (k_{mix}) for plain ice cream mix above the initial freezing point:

$$\mu_{mix} = k_{mix}\, \dot{\gamma}_{app}{}^{n_{mix}-1} \quad \text{D.25}$$

$$\mu_{wall} = k_{mix}\, \dot{\gamma}_{wall}{}^{n_{mix}-1} \quad \text{D.26}$$

The Reynolds number (Re) can be now calculated with Eq.D.27. The regime of agitation must be turbulent, so the Re value must be higher than 2,000. It can be controlled with the rotational speed of the blades (ω_t), increasing its value for achieving the minimum Re. Once the velocity of the turbine is set, the convection coefficient on the mix side can be calculated from *Eq.D.22*.

$$Re = \frac{{L_t}^2 \omega_t \, \rho_{mix}}{\mu_{mix}} \qquad \text{D.27}$$

D.4.2.2. Heat transfer on the jacket side (h_0)

The Davis equation applied for fluids flowing through the annular gap of concentric tubes, is a valid approximation for computing the convection heat transfer coefficient on the jacket size (Ocon and Tojo, 1980)

$$\frac{h_0}{c_p G} = 0.029 \left(\frac{D_i G}{\mu_{app}}\right)^{-0.2} \left(\frac{c_p \mu}{\lambda}\right)^{-2/3} \left(\frac{\mu_{app}}{\mu_{wall}}\right)^{0.14} \left(\frac{D_0}{D_i}\right)^{0.15} \qquad \text{D.28}$$

being G the mass flow of the heating fluid per unit of surface, D_0 and $D_i = D_v + \delta_v$ are the external and internal diameters of the annular gap. The difference of these two diameters is therefore the thickness of the jacket (δ_{jacket}), comprising the design variable for the heat transfer. The mass flow of fluid (hot water) used for heating a batch of mix would be:

$$G_w = \frac{\dot{M}_w}{N_{batch-day} \, {A^{annulus}}_{jk}} \quad ; \quad {A^{annulus}}_{jk} = \pi \left[\left(\frac{D_i + \delta_{jk}}{2}\right)^2 - \left(\frac{D_i}{2}\right)^2 \right] \qquad \text{D.29}$$

The rest of the parameters comprising *Eq.D.28* are the water properties at the considered heating temperature.

An iteration routine is set for computing the optimal thickness for the jacket that allows a h_0 value enough for achieving a design overall heat transfer coefficient by equation ($U_{Design}{}^{v-j}$) similar to the theoretical one. The lower the δ_{jacket}, the higher the h_0. A minimum thickness value of 0.01 m is assumed. When the minimum thickness doesn't provide a sufficient heat transfer coefficient, a jacketed vessel is not suitable for heating up the batch of mix at the pre-set time.

D.4.3. Design of an internal coil for heat transfer

The heat transfer can be implemented by using an internal coil that provides a higher heat transfer surface. An iron pipe size for the coil tube ($IPS_{tube}{}^{coil}$) of 2 inches is assumed, setting the internal diameter (D_{tube}^{coil}), the thickness (δ_{tube}) and the internal cross section (A_{tube}^{coil}) of the tube. Depending on the size of the vessel, the diameter of the internal coil (D_{coil}) is computed, and the level of the liquid within the vessel –i.e. equal to the diameter of the vessel (Walas, 1990)– will set the maximum number of turns for the coil (N_{turn}). A distance of one $IPS_{tube}{}^{coil}$ is assumed between walls and coil, and hence:

$$N_{turn}{}^{max} = \left\lfloor \frac{D_v}{2\ IPS_{tube}{}^{coil}} \right\rfloor \qquad \text{D.30}$$

$$D_{coil} = D_v - 2\delta_{tube} - 2IPS_{tube}{}^{coil} \qquad \text{D.31}$$

The heat transfer surface will be related to the circumference of the tube ($C_{tube}{}^{coil}$), the length of a single turn (L_{turn}) and the number of turns comprising the coil (N_{turn}):

$$A_{heat-trans} = N_{turn}\, L_{turn}\, C_{tube}{}^{coil} = N_{turn}(\,\pi\, D_{coil})\,\left(\pi\, IPS_{tube}{}^{coil}\right) \qquad \text{D.32}$$

The boundaries for the heat transfer surface are set by the minimum (1) and maximum (${N_{turn}}^{max}$) number of turns comprising the coil. For each integer N_{turn} within that range will provide a different $A_{heat-trans}$, and hence a different $U_{theoretical}$ following *Eq.D19*.

The calculation of the design overall heat transfer coefficient vessel-coil (${U_{Design}}^{v-c}$) is performed applying the heat transfer resistances model to the internal coil as follows:

$$\frac{1}{{U_{Design}}^{v-c}} = \frac{1}{h_i} + \frac{1}{f_{ic}} + \frac{\delta_{tube}}{\lambda_{ss}} + \frac{1}{f_w} + \frac{1}{{h_i}^{coil}} \quad \text{D.33}$$

h_i is computed following the procedure described in Section D.4.2.1. The heat transfer coefficient in the coil size (${h_i}^{coil}$) is described subsequently. The correlation of Dittus-Boelter for non-viscous fluids flowing inside a tube in turbulent regime, for a heating operation (Ocon and Tojo, 1980), is used:

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad \text{D.34}$$

When the tube is not straight as a coil, a correction factor ($F^{coil}_{correction}$) must be included in the correlation (McAdams,1942; Kern, 1983), so Eq.D.34 results in Eq.D36.

$$F^{coil}_{correction} = 1 + 3.5\,\frac{D^{coil}_{tube}}{D_{coil}} \quad \text{D.35}$$

$$\frac{{h_i}^{coil} D^{coil}_{tube}}{\lambda_w} = F^{coil}_{correction}\; 0.023 \left(\frac{\frac{\dot{m}_w}{N_{b-d}\, A^{coil}_{tube}}\, D^{coil}_{tube}}{\mu^w_{app}} \right)^{0.8} \left(\frac{{c_p}_{mix}\, \mu^w_{app}}{\lambda_w} \right)^{0.4} \quad \text{D.36}$$

The designed algorithm calculates the minimum number of turns comprising the coil for providing a sufficient ${h_i}^{coil}$, and hence a ${U_{Design}}^{v-c}$ similar to $U_{theoretical}$. If necessary, the algorithm could design a supporting heating jacket to the vessel. An extra flow of water will be required for providing the lack heat flow that the coil is not capable to supply ($\dot{Q}_{jk}$).

D.5. Continuous pasteuriser design

A plate heat exchanger is designed for this operation. The design procedure is based on Towler and Sinnot (2013) method, with some variations that will be mentioned along the text. First, the heat requirements of the system are given by the energy balance, being j the different food components of the ice cream mix.

$$\dot{Q}_{sensible} = \dot{m}_{mix} \sum_j \int_{T_{in}}^{T_{out}} x_j {c_p}_j dT \tag{D.37}$$

The effectivity of the regeneration is a parameter in this problem. Values up to 95% can be found in literature for milk products, taking a value of 80% to be on the safe side (Goff and Hartel, 2013). The temperature that the raw mix (pre-pasteurised) leaves the regenerator is calculated obtained from *Eq.D.38*, while the exit temperature of the homogenised mix is solved by iteration.

$$\eta_{reg} = \frac{T_{raw-reg}^{out} - T_{raw-reg}^{in}}{T_{hom-reg}^{in} - T_{raw-reg}^{in}} \tag{D.38}$$

Series flow model –a single pass (N_p=1) and one channel per pass ($N_{cp} = 1$)– and the standard heat exchanger specifications –plate spacing (e_{plate}=0.003m), plate width (a_{plate}=0.5m), length/width ratio (b_{plate}/a_{plate}=3) and thickness (δ_{plate}=0.0015m)–

comprise starting point of the system. This data allows to compute the heat transfer coefficient along a plate using the forced-convective heat transfer in conduits correlation.

$$h_{plate} = \frac{\lambda_{mix}}{d_h} 0.26 Re^{0.65} Pr^{0.4} \left(\frac{\mu}{\mu_{wall}}\right)^{0.14} = \frac{\lambda_{mix}}{d_h} 0.26 \left(\frac{G_p d_h}{\mu}\right)^{0.65} \left(\frac{c_{p_{mix}} \mu}{\lambda_{mix}}\right)^{0.4} \left(\frac{\mu}{\mu_{wall}}\right)^{0.14} \quad \text{D.39}$$

$$d_h = 4 \frac{S_{channel}}{wp_{channel}} \quad \text{D.40}$$

being G_p the mass flow rate per unit of cross-sectional area, and d_h the hydraulic diameter ($S_{channel}$ is the cross-section and $wp_{channel}$ is the wet perimeter of the channel). Different shear rates are taken for the mix flowing in the centre of the conduit $\dot{\gamma}_{app}$ and the one flowing close to the wall $\dot{\gamma}_{wall}$ –120 s^{-1} and 50 s^{-1} respectively (Goff and Hartel, 2013). The inner fluid has a higher shear rate as the effect of the friction due to the contact to the wall is lower. Once these values are set, the power law of the viscosity will compute the viscosity of the inner and wall fluid (*Eq.D.25 and Eq.D.26*) and Eq.D.39 can be solved.

Next step will be the calculation of the heat transfer surface using *Eq.D.19*. The logarithmic mean temperature should be corrected for PHE. For series flow model, the factor ($F_{correction}^{PHE}$) is 0.95. The total number of plates must provide the required surface value. N_p is constrained to be an even number and allowing an end-plate and an even number of passes.

Finally, the pressure drop within the heat exchanger is calculated as the sum of the pressure drop at the plates (Δp_p) and the pressure drop at the inlet ports:

$$\Delta P_p = 8 \times 0.6\, Re^{-0.3} \frac{l_{path}}{d_h} \frac{\rho v_p^2}{2} N_p \quad \text{D.41}$$

$$\Delta P_{pt} = 1.3 \frac{\rho v_{pt}^2}{2} N_p \quad \text{D.42}$$

where l_{path} is the path length ($L_{path} = N_p \times l_p$), is the volumetric velocity of the PHE ($v_p = G_p/\rho$) and v_{pt} is the velocity at the port ($v_{pt} = \dot{m}_{mix}/\rho A_{pt}$). A common port diameter is 0.1m, so the cross section of the port (A_{pt}) can be calculated for the pressure drop calculations.

D.6. Scrapped surface heat exchanger power consumption

Quin et al. (2006) developed a correlation for a SSHE in the refrigeration of ice slurries with change of phase. The torque increases with the ice fraction and therefore ice accumulated in the chamber. The dimensionless correlation, relating the Power number, rotational Reynolds, length and number of blades, adopts the following parameter values, found by trial and error based on their experimental data:

$$\frac{N_P}{L_{blades}} = 0.1\ Re^{-0.8} {N_{blades}}^{0.59} \qquad \text{D.43}$$

$$\frac{\dfrac{P}{\rho_{ic} {\varpi_{SSHE}}^3 {D_{stirrer}}^5}}{l_{blades}} = 0.1 \left(\frac{\rho_{ic} \varpi_{SSHE} D_{stirrer}}{\mu_{ic}}\right)^{-0.8} {N_{blades}}^{0.59} \qquad \text{D.44}$$

D.7. Tables called in the main text

Table D.2. Standard and premium ice cream ingredients composition. Carbohydrate are estimated by difference, according to the data sources.

Standard Ice cream

Stage	Ingredient	Mass fraction	Composition (%)			
			Fat	Protein	Carbohydrate	Water
Mixing (Chocolate & Vanilla)	Coconut oil**	0.150	100.0	-	-	-
	Skimmed milk powder*	0.120	0.7	36.0	60.3	3.0
	Sugar*	0.100	-	-	98.2	1.8
	Glucose Syrup*	0.030	-	-	80.3	19.7
	Glucose-Fructose Syrup*	0.020	-	-	76.0	24.0
	Guar gum**	0.002	-	-	90.0	10.0
	Carrageenan***	0.001	-	1.4	97.5	1.1
	Mono glycerides**	0.002	100.0	-	-	-
	Water	0.545	-	-	-	100.0
Flavouring (Chocolate)	Colorant solution*	0.002	-	-	3.0	97.0
	Cocoa Powder (in mix)**	0.030	13.7	19.6	63.7	3.0
	Chocolate liquor*	0.050	49.0	14.0	31.0	6.0
Flavouring (Vanilla)	Colorant solution*	0.002	-	-	3.0	97.0
	Vanilla extract**	0.003	0.1	0.1	47.2	52.6

* Goff and Hartel (2013)
****** USDA (2020**)**
******* Webber et al. (2012)

Table D.2. (cont.)

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

* Goff and Hartel (2013)
** USDA (2020)
*** Webber et al. (2012)

Table D.3. Results of the mass and energy balances for a plant comprising the Multi-Plant scale (26 plants) in a scenario analogous to the UK ice cream demand. Streams with hyphen belong to standard ice cream process, so they don't have flow here.

STREAM	1	2	3	4	5	6	7
TOTAL MASS (KG/H)	-	-	156.29	2.60	5.21	57.31	57.31
TEMPERATURE (K)	-	-	298.2	298.2	298.2	298.2	298.2
PRESSURE (BAR)	-	-	1.00	1.00	1.00	1.00	1.00
VAPOUR QUALITY	-	-	0	0	0	0	0
HEAT (KW)	-	-	-	-	-	-	-

STREAM	8	9	10	11	12	13	14
TOTAL MASS (KG/H)	5.21	651.20	708.50	26.05	-	-	260.48
TEMPERATURE (K)	298.2	298.2	298.2	298.2	-	-	298.2
PRESSURE (BAR)	1.00	1.00	1.00	1.00	-	-	1.00
VAPOUR QUALITY	0	0	0	0	-	-	0
HEAT (KW)	-	-	-	-	-	-	-

STREAM	15	16	17	18	19	20	21
TOTAL MASS (KG/H)	-	674.6	156.3	7.8	260.5	260.5	119.8
TEMPERATURE (K)	-	298.2	298.2	298.2	298.2	298.2	298.2
PRESSURE (BAR)	-	1.00	1.00	1.00	1.00	1.00	1.00
VAPOUR QUALITY	-	0	0	0	0	0	0
HEAT (KW)	-	-	-	-	-	-	-

STREAM	**22**	**23**	**24**	**25**	**26**	**27**	**28**
TOTAL MASS (KG/H)	1385.7	164.1	935.1	2604.8	-	-	-
TEMPERATURE (K)	298.2	298.2	298.2	298.2	-	-	-
PRESSURE (BAR)	1.00	1.00	1.00	1.00	-	-	-
VAPOUR QUALITY	0	0	0	0	-	-	-
HEAT (KW)	-	-	-	-	-	-	-

STREAM	**29**	**30**	**31**	**32**	**33**	**34**	**35**
TOTAL MASS (KG/H)	2604.8	2604.8	2604.8	2604.8	2604.8	2604.8	2604.8
TEMPERATURE (K)	298.2	341.7	352.6	352.6	309.2	277.2	277.2
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 (KW)	**102.03**		-	**– 102.03**		-	-
		25.67			**– 74.56**		

STREAM	**36**	**[...]**	**46**	**47**	**48**	**49**	**50**	**51**
TOTAL MASS (KG/H)	-		-	2604.8	7.2	249.5	256.7	2861.5
TEMPERATURE (K)	-		-	277.2	277.2	277.2	277.2	277.2
PRESSURE (BAR)	-		-	1.00	1.00	1.00	1.00	1.00
VAPOUR QUALITY	-		-	0	0	0	0	0
HEAT (KW)	-		-	-	-	-	-	-

STREAM	**52**	**53**	**54**	**55**	**56**	**57**	**58**
TOTAL MASS (KG/H)	0.21	2861.7	2861.5	282.82	183.00	465.82	3327.3
TEMPERATURE (K)	277.2	277.2	267.2	298.2	298.2	298.2	267.2
PRESSURE (BAR)	5.10	5.10	5.10	1.00	1.00	1.00	1.00
VAPOUR QUALITY	1	0	≈0	0	0	0	≈0
HEAT (KW)	-	**– 265.85**		-	-	-	-

STREAM	**59**	**60**	**61**	**62**	**63**	**64**	**65**
TOTAL MASS (KG/H)	3327.3	3327.3	0.21	2190.1	2190.1	7871,3	7871,3
TEMPERATURE (K)	267.2	248.2	298.2	363.2	353.2	275.2	285.2
PRESSURE (BAR)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
VAPOUR QUALITY	≈0	≈0	1	0	0	0	0
HEAT (KW)	**– 65.13**			**– 25.67**		**74.56**	

STREAM	**66**	**67**	**68**	**[...] 73**	**74**	**75**	**76**	**77**
TOTAL MASS (KG/H)	698.50	698.50	-	-	0.21	3.48 (m^3/h)	1182.97	1182.97
TEMPERATURE (K)	239.4	239.4	-	-	267.2	298.2	233.2	233.2
PRESSURE (BAR)	1.38	1.38	-	-	5.10	1.00	1.32	1.32
VAPOUR QUALITY	0	1	-	-	1	1	0	1
HEAT (KW)	**265.85**		-	-	-	-	**65.13**	

Table D.4. Features and variables of design of all the units involved in plant manufacture. The design variable is given in the cost correlation units.

Equipment	Feature 1	Feature 2	Design Variable	Power
High Shear Mixer	Length =2.43 m	Width = 2.53 m	V_{max} = 0.32 m^3	4.0 kW
Solid dilution Vessel	Diameter = 0.30 m	Height = 0.60 m	V = 12.36 gal(US)	15.7 W
Mixing Vessel	Length = 0.90 m	Width = 1.80 m	V = 333.66 gal(US)	2.5 W
PHE	a_p= 0.10 m	b_p= 0.30 m	N_p=2,593 $N_{channel/pass}$=1 l_{PHE}=11.67 m	-
Holding tube	Diameter=1.75 in	Length=13.25 m	t_{past}=30.2 s	-
Ageing Vessel (x3)	Diameter = 2.40 m	Height = 4.80 m	V =2903.3 gal(US)	-
Flavouring Tank	Diameter = 1.05 m	Height = 2.10 m	V =529.8 gal(US)	7.3 W
SSHE	Length = 8.79 m	Width = 2.00 m	N_b=3 r_{ce_i}=0.14 m c_b=0.20 ϖ_{SSHE}=2.82 s^{-1} N_{blades}=4	2.33 W
Packing Machine (x3)	Length = 3.80 m	Width = 0.80 m	Capacity = 3,000 unit/h	7 kW
Hardening Tunnel (x2)	Length = 2.20 m	Width = 0.60 m	Weight = 7,000 unit/h	17.5 kW
Boiler (gas)	Length = 4.00 m	Width = 2.50 m	$\dot{M}_{water}$= 4,828 lb/h	-

Table D.4. (cont.)

Cream Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Coconut Oil Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Soybean Oil Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Condensed Milk Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Sugar Silo	Diameter = 3.00 m	Height = 12.00 m	Weight = 12,838 kg	-
Molasses Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Guar Gum Silo	Diameter = 1.20 m	Height = 4.80 m	Weight =1,074 kg	-
Carrageenan Silo	Diameter = 0.75 m	Height = 3.00 m	Weight = 324 kg	-
Egg yolk Silo	Diameter = 1.35 m	Height = 5.40 m	Weight = 1,463 kg	-
Soya lecithin Silo	Diameter = 0.90 m	Height = 3.60 m	Weight = 512 kg	-
Vanilla Extract Silo	Diameter =1.20 m	Height = 2.40 m	Weight = 645 kg	-
Banana Puree Silo	Diameter = 2.40 m	Height =4.80 m	Weight = 4,148 kg	-
Chocolate Chunks Silo	Diameter = 3.45 m	Height = 13.80 m	Weight = 19,004 kg	-
Walnut Silo	Diameter = 3.30 m	Height = 13.20 m	Weight = 16,770 kg	-

Equipment Cost Correlations.

Table D.5. Correlation for equipment cost estimation (Matches, 2014).

Plate Heat exchanger	$p_{PHE} = 19{,}313\, A_{heat-trans}{}^{0.36}$	D.45
Agitator	$p_{agitator} = 3{,}929.1 \left(\frac{P}{745.7}\right)^{0.5}$	D.46
Scrapped Surface Heat Exchanger	$p_{SSHE} = -71.4\, A_{heat-trans}{}^{0.5} + 18{,}9\, A_{heat-trans} + 4{,}271.6$	D.47
Vessels	$p_v(\$_{2014}) = 975.6\,(264.2\, V_v)^{0.53}$	D.48
Packing Machine	Price 11,500 $ (Alibaba.com, 2019a) $p_{pack}(\$_{2019}) = N^o{}_{units} \times p$	D.49
Hardening Tunnel	Price 150,000 $ (Alibaba.com, 2019b) $p_{hard\ tunnel}(\$_{2019}) = N^o{}_{units} \times p$	D.50
Boiler	$p_{boiler}(\$_{2014}) = 11.20\, \dot{V}_w + 213{,}015$	D.51
Mechanical refrigerator	$p_{mech\ ref}(\$_{2010}) = 24000 + 3500 * \dot{Q}_{ref}{}^{0.9}$	D.52
Silos and storage tanks	$p_{silo}(\$_{2014}) = 231.50\, m_{silo}{}^{0.61}$	D.53
CEPCI index factors	$CEPCI_{2010} = 550.8\ ;\ CEPCI_{2014} = 576.1\ ;\ CEPCI_{2017} = 567.1$ $p(\$_{2017}) = p(\$_{2014}) \frac{CEPCI_{2017}}{CEPCI_{2014}}$	D.54

Table D.6. Raw materials price for Industrial (wholesaling) and Artisan (retail) manufacturing.

	Wholesaling prices		Retail prices	
	Price ($/kg)	**Source**	**Price ($/kg)**	**Source**
Molasses	0.10	Alibaba, 2019	5.28	Holland and Barrett, 2019
Glucose syrup	0.49	Alibaba, 2019	4.49	Cream Supplies, 2019
Glucose and fructose syrup	0.52	Alibaba, 2019	9.43	Amazon, 2019
Carrageenan	11.00	Alibaba, 2019	43.56	Amazon, 2019
Guar gum	4.00	Alibaba, 2019	30.10	Amazon, 2019
Coconut oil	0.55	Alibaba, 2019	14.62	Alibaba, 2019
Soybean oil	0.75	Alibaba, 2019	6.80	Amazon, 2019
Soy lecithin	1.15	Alibaba, 2019	34.22	Amazon, 2019
Cream	5.75	Alibaba, 2019	4.84	Tesco, 2019
Condensed Skimmed milk	1.20	Alibaba, 2019	1.77	Asda, 2019
Egg yolk (powder)	5.25	Alibaba, 2019	21.12	My protein, 2019
Skimmed milk powder	0.45	Alibaba, 2019	7.70	Sainsbury's, 2019
Monoglyceride	1.25	Alibaba, 2019	14.04	Breinbauer, 2019
Sugar	18.50	Alibaba, 2019	0.64	Asda,2019
Cocoa powder	1.20	Alibaba, 2019	9.50	Buy whole foods online, 2019
Vanilla extract	18.50	Alibaba, 2019	29.98	Asda, 2019
Banana puree	12.50	Alibaba, 2019	9.90	Funkin cocktails, 2019
Colorant	15.00	Alibaba, 2019	19.35	Meilleur du chef, 2019
Walnut	5.20	Alibaba, 2019	1093.20	Asda, 2019
Chocolate chunks	1.00	Alibaba, 2019	13.20	Amazon, 2019
Chocolate liquor	3.65	Alibaba, 2019	4.75	Waitrose, 2019
Water	$2.42\ 10^{-3}$ ($\$/m^3$)	South West Water, 2019	$2.42\ 10^{-3}$ ($\$/m^3$)	South West Water, 2019